EXPERIMENTAL STUDIES ON STIRRED ULTRAFILTRATION OF PROTEINS

A Thesis Submitted
In Partial Fulfilment of the Requirements
for the Degree of

DOCTOR OF PHILOSOPHY

BY

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to the

DEPARTMENT OF CHEMICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY KANPUR

MAY, 1978

CERTIFICATE

This is to certify that the work entitled 'EXPERIMENTAL STUDIES ON STIRRED ULTRAFILTRATION OF PROTEINS' has been carried out under our supervision and that it has not been submitted elsewhere for a degree.

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No man is an island and No mind is independent. It is only through a complex interaction, interdependence and interrelationship of a number of individuals that any meaningful scientific work is produced. It is so with the present work also and I consider myself to be just a cog in the wheel, may be an important one. I will be failing in my duty if I do not acknowledge the contribution of those who have made it possible.

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T. SWAMINATHAN

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A_M - Membrane Area

C - Local Solute Concentration

$\overline{C}, C_B$ - Upstream or Bulk Solute Concentration

C_p - Downstream or Permeate Solute Concentration

C_g - Gel Concentration

C'_s - Solute Concentration in the Membrane

C_W - Solute Concentration at the Upstream Membrane Surface or Wall Concentration

C_1 - Mean Concentration of Solvent in Membrane

d - Diameter of Particles in Gel Layer

D_s - Local Solute Diffusivity

D_1 - Diffusivity of solvent in Membrane

D_2 - Solute Diffusivity in Membrane

J_1 - Trans Membrane Solvent Flux

J_2 - Solute Flux

K_g - Mass Transfer Coefficient

K'_s - Dimensionless Coupling Coefficient

K_1 - Specific Permeability of the Membrane to the Solvent

K_1 - Constant in Kozeny-Carman Equation (Equation 2.23)

K_2 - Solute Distribution Coefficient between Membrane and Solution

$L(t)$ - Thickness of Gel Layer at Time 't'

M - Concentration Polarization Modulus

P	-	Pressure
P_c	-	Compressive Pressure
$\overline{P}_g$	-	Hydraulic Permeability of the Gel Layer
$\overline{P}_m$	-	Hydraulic Permeability of the Membrane
R	-	Retention Coefficient
R	-	Universal Gas Constant (in Equation 2.1)
R_g	-	Gel Layer Resistance
R_m	-	Membrane Resistance
t	-	Time of Filtration (in Equations 2.22 to 2.34)
t, t_m	-	Membrane Thickness (in Equation 2.1 to 2.10)
t_g	-	Gel Layer Thickness
t_{ss}, τ_{ss}	-	Time to Reach Steady State
T	-	Absolute Temperature
$V(t)$	-	Volume of Ultrafiltrate at Time 't'
$\overline{V}_1$	-	Partial Molar Volume of Solvent in Solution
x	-	Distance from the Diffusion-Gel Layer Interface Towards the Membrane
α	-	Specific Cake Resistance
δ_i	-	Boundary Layer Thickness
ε	-	Porosity
η	-	Viscosity
π	-	Osmotic Pressure
ρ_s	-	Solute Diffusivity
σ	-	Rentention Coefficient

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SYNOPSIS

With the development of high-flux anisotropic membranes with sharp cut-off, membrane ultrafiltration (UF) has emerged as an important molecular separation technique for a number of chemical process industries. It is finding increasing use for concentration, purification and separation of a wide range of macromolecular solutions.

A major problem encountered in UF, which is attributable to the high-flux characteristics of the membranes, is the problem of concentration polarization, i e. the accumulation of retained solutes on the membrane surface which always reduces the solvent flux through the membrane. In the case of macromolecules, such as proteins, the problem is further

complicated by the formation of a gel layer on the membrane surface. The phenomenon of concentration polarization has been the subject of many investigations and attempts have been made towards modelling of concentration polarization with a view to studying its cause, effects and techniques for its control, but many areas still remain to be explored.

In any UF experiment, the solvent flux decreases with time as a result of increasing polarization and reaches a steady value after a certain interval of time depending on the process conditions. Most of the UF data reported in literature are in the steady state gel polarized region and the effect of gel polarization has generally been studied with a pre-formed gel layer.

To gather fundamental information on the process of concentration polarization and its effect on membrane performance it is necessary to study the UF performance in the transient period, before a steady state is reached. Further, to understand the effect of various parameters on the UF performance, investigations should be made in the pre-gel polarized region also, since concentration polarization, though it still affects the membrane performance, does not always lead to gel formation.

The concentration polarization in UF of protein solutions has been investigated in the present study with a magnetically stirred UF cell fabricated from acrylic plastic.

The solutes, membranes and the experimental conditions used were:

Solutes: Ovalbumin, Bovine Serum Albumin, Egg Albumin, Hemoglobin and Poly Ethylene Glycol.

Membranes: Amicon Diaflo PM 30, XM100A and XM300.

Pressures: 10, 20 and 35 psig.

Solute concentrations: 0.05, 0.1 and 0.5 percent (by weight)

Initial time studies were conducted to study the process leading to gel polarization, its effect on UF flux and solute retention, the time required to attain steady state and the effect of UF parameters on this time. The effects of several system parameters, e.g., pressure, bulk solute concentration, membrane permeability, stirring and solute molecular size were investigated in the gel polarized as well as the pre-gel polarized regions and were analysed in the framework of the gel polarization and pre-gel polarization models proposed by Michaels and coworkers. The polarized layer resistance and the pressure drop in the polarized layer were calculated. The experimental results were also used to verify the suitability of an approximate theoretical analysis of gel layer build up proposed along the lines of classical filtration theory.

Steady state ultrafiltration studies were carried out with 0.25 and 1.0 percent protein solutions at 20 psig with all the membranes. The variables studied were solute

concentration, pH and membrane treatment with a non-ionic detergent. The pH of the solution was chosen as a variable as proteins are dipolar and pH has a strong effect on their structure and physical properties. Treatment with detergent was studied since these well-studied membranes were found to exibit some unusual behaviour after detergent treatment in some preliminary experiments.

CHAPTER 1

INTRODUCTION

During the last decade, membrane ultrafiltration (UF) has been transformed from a mere laboratory curiosity into a most promising molecular separation technique. The concentration, purification and separation of macromolecules by UF is finding increasing use in food processing, petroleum, pharmaceutical, polymer and paper making industries as well as in water and waste treatment. Production applications of UF have been reviewed by Michaels [59], Van Altena [72], Bansal [6] and GoldSmith [41].

Ultrafiltration is a relatively simple process in which the feed solution containing macromolecular solutes is introduced into a membrane separator where solvent and certain solutes pass through a semipermeable membrane under an impressed pressure gradient and are collected as ultrafiltrate. Solutes whose sizes are larger than the largest pore opening in the membrane are retained on the membrane and are collected as retentate. Nearly complete separation of any desired solute from the solvent can be ensured by properly selecting the membrane, the sole energy requirement being the compression energy of the feed solution.

Although some of the applications of UF are unique, the increasing use of UF over other competing processes such as

evaporation, drying, ultracentrifugation, dialysis, gel filtration, chemical precipitation etc. is due to the following advantages [8,41]: (a) It is athermal; (b) it involves no phase change; (c) it is relatively nondestructive and therefore particularly attractive for food processing; (d) since the operating pressure is low, process energy requirement is quite limited; (e) the process is simple and versatile; (f) its modular nature makes it economical at both small and large sizes.

The emergence of UF as a viable industrial process was almost entirely due to the development of anisotropic, high-flux membranes [58] with sharp cut-off characteristics. The graded pore structure of such membranes with a thin skin of small pores supported by a much thicker layer of relatively large pores ensures high solvent flux with high retentivity while avoiding almost totally any entrapment of solutes within the porous network [63]. However, the fullest exploitation of the high flux characteristics of such membranes has been hampered by the phenomenon of concentration polarization. Encountered in almost all membrane separation processes , concentration polarization is the accumulation of retained solutes on the high pressure side membrane surface. This layer of retained solutes is an additional resistance to solvent flow so that the solvent flux is reduced at any pressure from the ideal level. In the case of macromolecular solutes, such as proteins, the phenomenon of

concentration polarization acquires an additional dimension due to the unusual property of proteins which form a gel layer at high concentrations. Under such conditions, solvent flux in UF becomes invariant with increase in pressure and the phenomenon is known as gel polarization.

The problem of concentration polarization has been long recognized in UF work. But attempts to eliminate it have not always been successful, so that most studies on process applications of UF present data in the gel polarized region. Modelling of concentration polarization phenomenon with a view to evaluating the parameters governing it and the methods for its control has also attracted considerable attention. Though elaborate analyses for micro and macro-solute polarization have been developed, among others, by GoldSmith et al.,[41], Michaels [58], Gill [38], Dresner [30] and Blatt et.al., [15], many areas still remain to be explored.

For a proper understanding of the problem of gel polarization, a knowledge of the mechanism of the gel formation as well as the effect of gel polarization on UF performance is essential. It is also well known that the gel polarization eventually controls the UF process and always adversely affects the efficiency and the rate of UF process. Thus, for a reasonable evaluation of the membrane, the UF system and the efficiency of techniques to reduce polarization, it is necessary to distinguish

between the membrane controled UF performance and the gel controled UF performance.

Experimental investigations on the nature of the gel layer and the effect of gel polarization on UF performance have been reported in the literature [15,27,29]. In these studies, the gel layer was formed on the membrane prior to its investigation. The effect of the parameters such as pressure and bulk solute concentration on gel layer controled UF process has also been well studied. But the process of formation of the gel layer and the effect on membrane performance as the gel layer is formed have not been given adequate attention. This is probably due to the fact that under the concentration and pressure conditions usually employed in UF work, the gel layer is formed within a very short time, usually less than a minute [27,60].

According to the gel polarization model proposed by Michaels et al. [15], the solvent flux in UF decreases with time due to polarization and eventually reaches a steady state. To gather fundamental information about the process of gel polarization and its effect on membrane performance, investigation of UF performance in the transient period, before a steady state is reached, is essential. This is termed the initial time studies. Such studies also provide knowledge of the time required to attain steady state and the effect of UF parameters on this time. These are required to evaluate the efficiency of polarization control

techniques and to determine the time after which the system output is of acceptable quality, particularly in the case of partially retentive membranes. Since gel polarization takes place with in a short time under normal conditions, it is necessary to work with dilute solutions at low pressures so that the time taken to reach steady state will be measurable and sufficient filtrate could be collected for retention studies.

According to the gel polarization model, the gel layer, when formed, controls the UF process. But polarization does not always result in gel formation and there is a region, particularly at lower pressures and concentrations, in which the membrane still controls the UF process at steady state, though polarization affects the membrane performance. This is known as the pre-gel polarized region [15]. A knowledge of the membrane performance in this region is necessary to make a comparative evaluation of different membranes and to understand the effects of various parameters on UF performance as the gel layer is formed. Unfortunately, limited information is available in the literature on the UF behaviour in the pre-gel polarized region. The reason for this could be that, in general, UF is conducted with totally retentive membranes and at the moderate conditions commonly used, gel polarization always takes place. To study the pre-gel polarization also it is necessary to work at low pressures and with low solute concentrations. These studies

form the first part of the present investigation.

Steady state UF of macromolecules has been widely reported in the literature, the parameters studied being pressure, solute concentration, temperature, geometrical factors and fluid dynamic conditions. With solutes such as proteins, additional parameters like pH, ionic strength or chemical treatment will have considerable effect on UF performance since they affect the structure of the solute and solute-membrane interactions. These have not received adequate attention from experimental investigators. The steady state UF of proteins was studied in this work with concentration and pH as the variables and constitutes the second part of the present investigation. The effect of membrane treatment with a non-ionic detergent on UF performance was also studied in steady state UF as it was suspected that such a treatment may alter the membrane performance.

Since UF is essentially a sieving process, it is beleived to be similar to classical cake filtration, the major apparent difference being one of scale of dimensions of solutes being separated. This similarity is only superficial and the engineering principles which govern efficient UF and classical filtration are radically different [58]. In classical filtration, the filter medium is not the primary barrier but functions as a hydraulically permeable support for the cake of retained solutes,

which itself is permeable and controls the filtration process. The filtration products are a filtrate and a solid or semi-solid cake whereas in UF the membrane functions as the sole solute barrier and the UF products are two liquid phases, a solute depleted ultrafiltrate and a solute enriched retentate. For an efficient UF the accumulation of solute on the membrane surface must be avoided. But in actual practice, it is known that in UF of macromolecules, such as proteins, the accumulation of solutes does take place resulting in a cake of retained solutes which is permeable and controls the UF process. It is possible, then, that the theory of classical filtration may have some use in modelling of cake formation due to polarization in UF. In the third part of the present investigation an attempt has been made to propose an approximate model for the gel layer build up based on the theory of classical filtration and to verify some of the features of the model experimentally.

CHAPTER 2

ULTRAFILTRATION THEORY

An understanding of the basic transport processes is essential for any practical application of ultrafiltration. This must include consideration of transport in the fluid phases adjacent to the membrane as well as transport within the membrane itself. The mass transport mechanisms by which the solute and the solvent are transported through the membrane are presented in the first part of this chapter while the second part deals with the transport behaviour in the fluid phase, in particular, the problem of concentration polarization and its modelling.

2.1 Transport Kinetics in Ultrafiltration:

Two basic classes of mass transfer mechanisms have been identified in ultrafiltration membranes depending, mainly, upon the sizes of solutes to be ultrafiltered. Membranes which retain rather small molecules, i.e., those of molecular weight under ca.500 or of molecular dimensions under 10 A^o, function as diffusive transport barriers. In these membranes both solute and solvent are transmitted by molecular (Fickian) diffusion as a result of chemical potential gradients established in the membrane by the applied pressure and concentration differences. On the other hand, membranes capable of retaining relatively large solute molecules, i.e., those of molecular weight above

500 or of molecular dimensions above 10 A°, appear to function as molecular sieves or screens. The solvent moves, through the micropores in these membranes, in essentially viscous flow while solute molecules are carried convectively with the solvent, but only in pores whose dimensions are large enough to accomodate them. The transport mechanisms for both types of membranes have been worked out by Michaels and coworkers [15,57,58] and are presented below.

Diffusive Ultrafiltration:

For diffusive type membranes, the steady state relationships governing the solvent and solute transport are, to a first approximation, as follows [56].

For solvent

$$J_1 = K_1/t\ (\Delta P - \Delta \pi) = \frac{\bar{C}_1 D_1 \bar{V}_1}{t\ RT}\ (\Delta P - \Delta \pi) \qquad (2.1)$$

where

J_1 = Solvent flux (ml./cm^2 sec.)

t = Membrane thickness (cm.)

K_1 = Specific permeability of the membrane to the solvent

ΔP = Hydrostatic pressure difference across the membrane (dynes/cm^2)

$\Delta \pi$ = Solute osmotic pressure difference between the upstream and downstream solutions (dynes/cm^2)

$\bar{C}_1$ = Mean concentration of solvent in membrane (gm./cm^3)

D_1 = Diffusivity of solvent in membrane (cm^2/sec.)

$\bar{V}_1$ = Partial molar volume of solvent in solution (cm^3/mole)

R = Universal gas constant

T = Absolute temperature

According to Schlögl, Staverman and others [57] equation(2.1) should be modified by the insertion of a reflection coefficient as a multiplier of $\Delta\pi$, although for sufficiently dilute solutions (when $\Delta\pi << \Delta P$) this correction is of little importance.

For solute

$$J_2 = -D_2 \frac{dC'_s}{dt} + K'_s \frac{J_1 C'_s}{\bar{C}_1} \qquad (2.2)$$

where

J_2 = Solute flux

C'_s = Solute concentration in the membrane

K'_s = Dimensionless coupling coefficient

The first term on the right hand side of equation (2.2) represents the normal diffusive flux of solute through the membrane where D_2 is the local diffusion coefficient of the solute in the membrane. The second term accounts for the so called coupling of solute and solvent tranport which in essence is the convective flux of solute driven by the net flow of solvent.

Equation (2.2) can be integrated with the following assumptions: (i) Membrane-solution equilibrium is established at

both boundaries of the membrane, (ii) the solute diffusivity is essentially independent of concentration and (iii) the distribution coefficient of solute between the membrane and the solution is constant ($C'_s = K_2 C_s$).

Integration over the thickness of the membrane will yield

$$J_2 = \frac{K_2 K'_s J_1}{\overline{C}_1} \left[\frac{C_B - C_P \quad \exp\,(-K'_s J_1 t/\overline{C}_1 D_2)}{1 - \exp\,(-K'_s \; J_1 t/\overline{C}_1 D_2)} \right] \qquad (2.3)$$

For the diffusive membrane, the coupling can be neglected and equation (2.3) reduces to

$$J_2 = \frac{K_2 \; D_2}{t} \; (C_B - C_P) \qquad (2.4)$$

where

J_2 = Solute flux ($gm/cm^2 sec.$)

K_2 = Solute distribution coefficient between membrane and solutions

D_2 = Solute diffusivity in membrane

C_B = Upstream solute concentration (gm/cm^3)

C_P = Downstream solute concentration (gm/cm^3)

For perfect crossflow, the solute mass flux J_2 is related to the volumetric solvent flux J_1 by

$$J_2 = J_1 \; C_P \qquad (2.5)$$

On the basis of conservation of solute species. For a highly

retentive membrane ($C_P << C_B$) equations (2.1,2.4 and 2.5) can be solved simultaneously to give

$$R = 1 - C_P/C_B = \frac{B(\Delta P - \Delta \pi)}{1+B\ (\Delta P - \Delta \pi)} \qquad (2.6)$$

where

$$B = \frac{K_1}{K_2 D_2}$$

This quantity R is the retention coefficient. It indicates that fraction of the solute present in the feed solution which is held back by the ultrafilter.

It is evident that the solvent flux through the diffusive type membrane is directly proportional to the effective pressure difference across the membrane, while the solute flux is not directly pressure dependent. On the other hand, the retention coefficient increases with increasing pressure approaching the theoretical limit of unity as the applied pressure increases to infinity. In actuality, however, there is some coupling of solute and solvent flow leading to increased solute permeability. As a result, the retention coefficient does not reach unity but rather approaches an asymptotic value less than unity. If the solute permeability is sufficiently small relative to the solvent permeability, the membrane will reach this asymptotic behaviour at quite low pressures.

Furthermore, for diffusive membranes, the retention efficiency of solutes of similar chemical structure will generally increase with increasing size of solute molecules. For solutes of dissimilar chemical structure, molecular size alone is not sufficient to predict the retention efficiency since the affinity of the solute for the membrane substance is an equally important factor.

Microporous Ultrafiltration

For microporous, sieve type membranes, the solvent and solute transport relationships are:

For solvent,

$$J_1 = K_1 \Delta P / \eta t \tag{2.7}$$

where η = Solvent viscosity

For solute,

$$J_2 = C_B(1-\sigma) J_1 = C_B (1-\sigma) K_1 \Delta P / \eta t \tag{2.8}$$

where σ = A dimensionless constant ($0 < \sigma < 1$) dependent on the solute size and the membrane pore size distribution.

Applying the continuity equation for solute species $J_2 = J_1 C_P$ we get from equations (2.7 and 2.8)

$$R = 1-C_P/C_B = \sigma \tag{2.9}$$

It is obvious from these relationships that the solvent flow varies linearly with the hydraulic pressure difference and the retention coefficient is independent of applied pressure

difference. Since, the osmotic pressure of the high molecular weight solute retained by the membrane is usually very small compared with the applied pressure difference, no quantity involving osmotic pressures appear in relations 2.7, 2.8 and 2.9 .

The quantity σ represents physically, the fraction of the total liquid flowing through the membrane and passing through the pores large enough to accomodate the solute molecules. Since this parameter is determined solely by the solute molecular dimensions and the pore size distribution in the membrane, the membrane retention coefficient should be independent of applied pressure and concentration. But it is frequently found that membranes display anomalous behaviour.

In some cases the retention coefficient decreases with increasing pressure [4]. This may be due to an increase in pore size as a result of elastic distortion of the membrane or shear induced distortion or uncoiling of the solutes such that they can pass through small pores. With some membranes, retention efficiency has been found to increase with increasing feed solution concentration. This has been attributed to the reduction in flow through pores large enough to pass the solute molecules due to the extra viscous drag by the solute molecule in the pore, which biases the flow in favour of pores too small to accomodate the solute, thereby increasing the retention [58].

2.2 The Problem of Concentration Polarization and Its Modelling:

2.2.1 Concentration Polarization:

It has been usually observed that when a solution is ultrafiltered at any pressure through a high permeability membrane which retains the solute completely or partially there is a drastic reduction in the solvent flux, compared to the value measured with the pure solvent under similar conditions. This flux reduction is not attributable to the plugging of UF membranes ultrafiltration (UF) membranes [60].

During ultrafiltration of a solution through a membrane, the convective flux of the solute towards the membrane with the solvent initially exceeds the rate at which the solute passes through the membrane resulting in accumulation of the solute near the upstream surface of the membrane. A steady state will ultimately be reached wherein any solute convectively transported towards the membrane must be removed by passage through the membrane and by diffusive transport away from the membrane into the bulk of the upstream fluid. The consequence of these interacting transport processes is the development of a layer of solution, highly concentrated in the retained solute (in comparison to the bulk solution) on the upstream surface of the membrane. This is the phenomenon of 'concentration polarization' which is common to every mass transfer process occurring across a semipermeable barrier [57].

The effect of polarization upon membrane performance is always adverse and frequently severe. Since the membrane responds, in its transport behaviour, only to the immediate boundary conditions it 'sees', it naturally displays the solvent and solute transport characteristics of this layer of more concentrated upstream solution. If the membrane is not completely solute impermeable, polarization results in solute flux much greater than that would be predicted from the bulk solution concentration, resulting in decreased retention efficiency. Further, if the solute is of relatively low molecular weight, the highly concentrated polarized layer increases the solute osmotic pressure,therby reducing the effective driving force and thus reducing the ultrafiltration flux. If the solution contains high molecular weight solutes or colloids, concentration polarization produces a layer of finite and,frequently,large hydraulic flow resistance resulting in substanxial reduction in UF rate.

2.2.2 Modelling of Concentration Polarization:

The adverse effect of concentration polarization on the membrane performance has long been recognized. Much effort has been devoted to the modelling of the concentration polarization phenomenon with a view to understanding the operational parameters controlling the polarization and to reduce, if not eliminate,

polarization. Elaborate mathematical analyses of microsolute polarization, e.g., reverse osmosis desalination of water, in both laminar and turbulent flow in cylinderical and parallel plate channels have been made by Dresner[30], Gill [38], Sherwood and Brian [66] and others. This analysis has been extended to concentration polarization in UF of macromolecules and proteins by Blatt et al.[15], Dejmek [27], GoldSmith et al.[41] and Michaels [58].

The general model for concentration polarization is described in this section while some peculiar effects of concentration polarization in the UF of proteins are described in the next section.

The conditions which exist within a typical polarized layer with microsolutes are shown schematically in Figure 2.1. A few simplifying assumptions are made, which allow the concentration polarization to be described by a simple boundary layer theory. The membrane surface in contact with the solution is considered to be smooth, convection due to local density gradients is neglected, and a concentration independent solute diffusivity is assumed. The bulk solution is well stirred with a constant solute concentration $\overline{C}$ and the velocity and concentration gradients are restricted to the region traditionally termed as the laminar boundary layer.

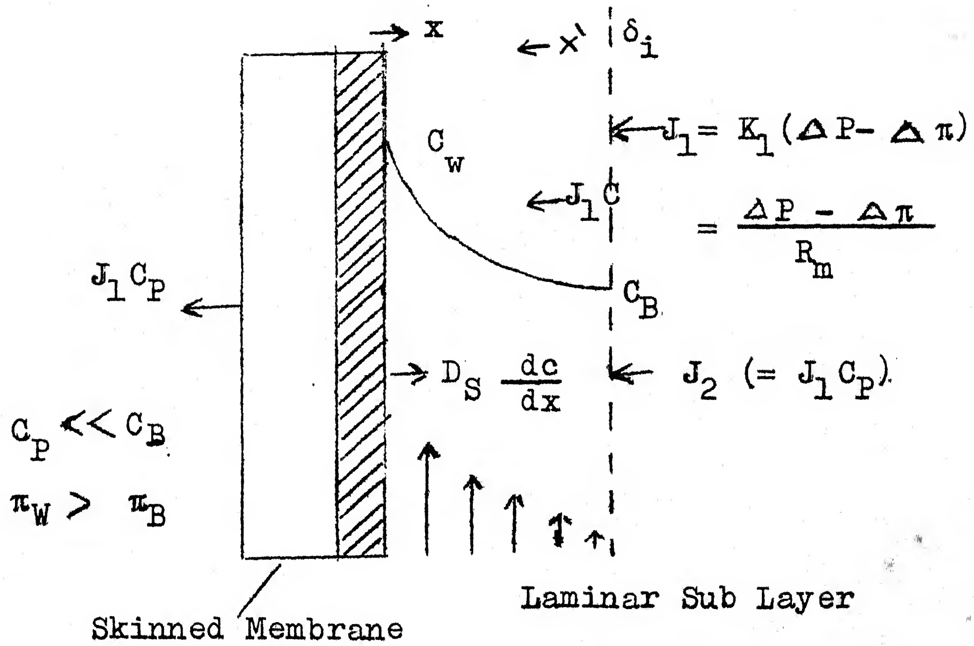


Figure 2.1 Schematic Diagram of Concentration Polarization with Microsolutes

In the steady state, the solute concentration profile is constant and the convective solute transport to the membrane is balanced by the diffusive salt flux from the interface to the bulk solution and the solute flux through the membrane. The solute balance is given by

$$J_1 C - D_s \, dC/dx - J_1 C_p = 0 \qquad (2.10)$$

where

J_1 = Transmembrane solvent flux ml./cm² sec.

C = Local solute concentration gm/cm^3

D_s = Local solute diffusivity cm^2/sec.

x = Normal distance from the membrane surface cm.

C_p = Solute concentration on the downstream side gm/cm^3

Integrating equation (2.10) over the thickness of the boundary layer and applying the boundary conditions, one gets

$$\ln \frac{C_w - C_p}{\bar{C} - C_p} = \frac{J_1 \delta_i}{D_s} \tag{2.11}$$

where δ_i = Boundary layer thickness cm.

C_w = Solute concentration at the upstream membrane surface gm/cm^3

For membranes rejecting the solute completely $C_p \ll \bar{C} < C_w$ and equation (2.11) reduces to

$$\ln \frac{C_w}{\bar{C}} = \frac{J_1 \delta_i}{D_s} \tag{2.12}$$

For solute transfer in the absence of water removal, D_s/δ_i can be replaced by a solute mass transfer coefficient K_s^o. The concentration polarization modulus M is then given by

$$M = \frac{C_w}{\bar{C}} = \exp\left(\frac{J_1 \delta_i}{D_s}\right) = \exp\left(J_1/K_s^o\right) \tag{2.13}$$

This relation indicates that the polarization modulus increases exponentially with the transmembrane flux and the

boundary layer thickness and decreases exponentially with increasing solute diffusivity. This means that polarization is particularly severe with high solvent permeability membranes and high molecular weight solutes.

It is assumed that K_s^o is unaffected by the small water flux J_1. Correlations for mass transfer coefficient K_s^o have been made, using Chilton-Colburn analogy for various flow geometries and flow regimes by Brian [16], Kimura [47], Sherwood et.al.[66] and for stirred cells by Colton [20].

This boundary layer model gives an oversimplified picture of the boundary layer transport phenomenon. Nevertheless, it describes the concentration polarization in a turbulent flow cell and in a well stirred batch cell with sufficient accuracy. Fisher [35] has shown that more sophisticated models that assume the occurance of molecular or eddy diffusion in the boundary layer also lead to approximately the same results.

2.2.3 Concentration Polarization in Protein Ultrafiltration-Gel Polarization Model:

In the UF of solutions of macromolecules such as proteins or colloidal dispersions, the concentration polarization, though governed by the same mass transport and fluid mechanical factors that govern the microsolute polarization, has been found to exhibit some pecular effects. It has been found that for most

macromolecular solutions, the membrane fluxes are significantly lower than those measured for water at the same operating conditions. This cannot be attributed to the osmotic pressure effects since the osmotic pressures of these solutes are very low even at high concentrations. Another feature noted in the UF of macrosolutes is that beyond a threshold pressure, the UF fluxes are independent of pressure in contrast to the linear increase of pure water flux with pressure.

The peculiar effects of macro-solute or colloid polarization on UF are in a large measure attributable to the unusual properties of concentrated solutions of these substances. For these solutions, the viscosity increases with increasing concentration and above a certain concentration (characteristic of the particular solute), known as the gel concentration, the solutions cease to behave as newtonian fluids. Rather they behave as a viscoelastic solid or a viscoelastic fluid(Bingham type), i.e., they distort elastically under shear and rupture at characteristic shear stress or they deform elastically at low shear stresses and flow as highly viscous fluids above a critical stress.

To explain the peculiar effects of polarization during UF of macromolecular solutions, Michaels proposed a modified model of concentration polarization known as 'gel polarization'

model [15,58]. A schematic representation of this model is shown in Figure 2.2. In this model also the solute retention at

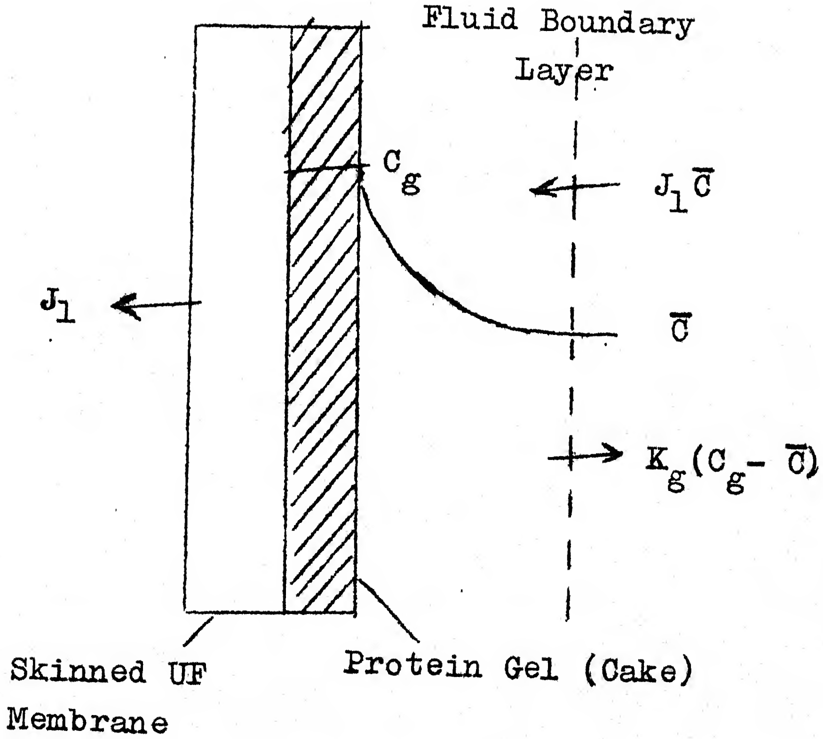


Figure 2.2 Schematic Representation of Gel Polarization Model

the membrane surface results in the formation of a concentrated layer of solutes in contact with the membrane and the solute concentration at that surface rapidly reaches a constant value known as the gel concentration (which depends upon the chemical

and morphological properties of the solute and is typically in the range of 20-60 percent] which is virtually independent of bulk concentration, pressure, fluid flow conditions or membrane characteristics. The rheological and mechanical properties of this layer of solutes is substantially different from those of the contiguous solution. This layer is the commonly observed 'slime' or 'cake' adhering to the membrane surface. Because of its high viscosity, it either does not migrate with the flowing upstream fluid or else it moves with a much lower velocity relative to the flowing fluid. In effect, the gel layer interposes between the membrane and the solution, a secondary membrane which is hydraulically permeable to the solvent Since, in general, the hydraulic permeability of such a gel layer is smaller than that of the UF membrane itself, a substantial fraction of the applied pressure is sustained through the gel layer and correspondingly the net solvent flux through the membrane is reduced.

At steady state, however, as in the case of microsolutes, the UF rate is determined by a balance between the forward convective transport of solute to the gel layer and the backward diffusive transport of the solutes from the gel layer into the bulk solution. This balance may be expressed by the equation

$$J_1 \overline{C} = K_g^o \ln C_g/\overline{C} \qquad (2.14)$$

where

$\overline{C}$ = Bulk concentration gm/cm^3

K_g^o = Mass transfer coefficient (cm/min.)

C_g = Gel concentration gm/cm^3

Since the gel concentration C_g is constant, the back transport rate reaches a limiting value, governed only by the fluid mechanical properties of the UF system. This means that the UF rate is governed solely by the solute mass transfer conditions and is virtually independent of applied pressure and the actual membrane permeability. Parameters which enhance the back transport such as increased fluid velocity or reduced channel height in flow systems and more rapid stirring in stirred cells increase the net UF rate.

According to the gel polarization model, with macromolecular solutions, a gel layer sticking to the membrane surface results in a considerable reduction in UF flux, due to the additional hydraulic resistance offered by the layer. A comparison of the resistances of the gel-layer and the UF membrane will give an idea of the effect of polarization. The gel layer-membrane composite can, to a reasonable approximation, be treated as two hydraulic resistances in series. The UF flux J_1 can be related to the applied pressure, ΔP, by the relation

$$J_1 = \Delta P/R \qquad (2.15)$$

where the resistance R, is given by

$$R = R_m + R_g \tag{2.16}$$

where R_m = The membrane resistance

R_g = Gel layer resistance

The membrane resistance, R_m, can be determined from the pure solvent flux, J_1^o, and is given by

$$J_1^o = \frac{\Delta P}{R_m} = \frac{\bar{P}_1}{t_m} (\Delta P) \tag{2.17}$$

where $\bar{P}_1$ = Hydraulic permeability of the membrane

t_m = Thickness of the membrane

It the gel layer has a specific hydraulic permeability, P_g, and thickness, t_g, then the flux through the laminate is given by

$$J_1 = \frac{\Delta P}{R_m + R_g} = \frac{\Delta P}{t_m/P_m + t_g/P_g} \tag{2.18}$$

From equations (2.16) and (2.17)

$$J_1 = \frac{J_1^o}{1+(P_m t_g/P_g t_m)} = \frac{J_1^o}{1 + R_g/R_m} \tag{2.19}$$

Then, at steady state

$$J_1 = \frac{\Delta P}{R_g + R_m} = \frac{\Delta P_g}{R_g} = \frac{\Delta P_m}{R_m} \tag{2.20}$$

where P_g = Pressure drop in gel layer

P_m = Effective pressure drop across the membrane

If the gel layer resistance is much higher than the membrane resistance, the flux observed will be only a small fraction of that obtained when only pure solvent is ultrafiltered.

The gel layer resistance has been shown to be a function of the hydraulic permeability of the gel layer. The hydraulic permeability of the gel layer is a complex function of the solids concentration and of such variables as the size, shape and state of aggregation of molecules comprising the solid phase. For relatively concentrated dispersions of nearly isometric (spherical) particles, the hydraulic permeability for a solvent with viscosity, η, can be approximated by the Kozeny-Carman relation for porous solids and is given by [15]

$$P_g = \frac{d^2 \varepsilon^3}{180 (1-\varepsilon)^2 \eta} \tag{2.21}$$

where d = Diameter of particle

ε = The porosity of the gel layer

It is obvious that the permeability of the gel layer is a strong function of the porosity and particle size.

The gel polarization model has been extensively used to explain the UF performance of macromolecular and colloidal systems by many investigators and these are discussed in detail in Chapter 4 along with the results of the present investigation.

2.2.4 Model of the Gel Layer Build up:

It was described in the previous section that, in the UF of macromolecular solutions, concentration polarization results in a gel layer formation. The state of gel polarization is achieved after an initial unsteady state during which both the gel layer as well as the diffusional layer are formed. The diffusional layer, here, refers to the concentration boundary layer in Figure 2.2, where the concentration is changing from C_g to $\bar{C}$. It would be of interest to know the time taken to achieve the steady state, the volume of ultrafiltrate during this time and the nature of changes with time of the solvent flux and solute retention. In this section, an attempt is made to propose a model, from the theory of classical filtration, relating these quantities.

Since the resistance of the gel layer is usually much more than that of the diffusional layer in the gel polarized region, it would be reasonable to expect that the time required to form a diffusional layer would be very much shorter. In the following analysis, the time required to reach the gel concentration is first neglected and the attention is focussed on the phenomenon of the gel layer build up. During the initial period, since the forward solute flux is greater than the back diffusion flux, the thickness of gel layer of retained solutes increases. A steady

state is attained in this constant pressure UF when the solvent flux is low enough for the back diffusion rate of solute to match the rate of solute retention by the membrane. While, in classical constant pressure filtration, the cake build up continues with time, the cake build up in UF ceases when the steady state is reached. However, the concentration of the bulk solution $\overline{C}$ increases with time, for example, in batch stirred cell UF.

A solute balance around the gel and the diffusion layer for a batch stirred UF leads to

$$\int_0^t [\ \overline{C}\ (t) - C_p\ (t)\ ]\ dV(t) - K_g A_M \int_0^t [\ C_g - \overline{C}\ (t)\ ]\ dt = A_M\ \rho_s \int_0^{L(t)} (\ 1 - \varepsilon)\ dx' \qquad (2.22)$$

where $V(t)$ = Volume of ultrafiltrate from time t=0,ml.

A_M = Membrane area, cm^2

ρ_s = Density of solute material, gm/cm^3

ε = Porosity of the gel layer at location x

x' = Distance from the diffusion-gel layer interface towards membrane (Figure 2.2),cm

$L\ (t)$ = Thickness of gel layer at time t, cm

and t = Time from the beginning of UF, seconds

The equation (2.22) has been formulated such that

a compressible cake may be assumed, since Dejmek [27] and Dorson et al.[29] have found the protein gel layers in UF to be compressible. The solvent flux through the cake may be related to the pressure drop dP through a differential thickness dx' of the cake, of porosity ε (the cake being made of spherical solute molecules of diameter d) by the Kozeny-Carman equation [23]

$$\frac{1}{A_M}\left(\frac{dV(t)}{dt}\right) = J_1(t) = \frac{\varepsilon^3 d^2}{K_1(1-\varepsilon)^2\,\eta}\left(-\frac{dP}{dx'}\right) \qquad (2.23)$$

Defining the quantity α by

$$\alpha = \frac{K_1(1-\varepsilon)}{\varepsilon^3 d^2 \rho_s} \qquad (2.24)$$

and substituting for $d\hat{x}'$ from equation (2.23) in equation (2.22) leads to

$$\int_0^t [\bar{C}(t) - C_p(t)]\,dV(t) - K_g A_M \int_0^t [C_g - \bar{C}(t)]\,dt$$

$$= \frac{A_M}{J_1(t)} \int - \frac{dP}{\alpha\eta} \qquad (2.25)$$

However, in terms of a pseudo-compressive pressure on solids in the gel P_c [70],

$$d\,P_c + dP = 0 \qquad (2.26)$$

Equation (2.25) then reduces to

$$\int_0^t [\bar{C}(t) - C_p(t)]\,dV(t) - K_g A_M \int_0^t [C_g - \bar{C}(t)]\,dt$$

$$= \frac{A_M}{J_1(t)\eta} \int_0^{\Delta P_{gel}} \frac{dP_C}{\alpha}$$

The quantity α, known as the specific cake resistance, can be related to the compressive pressure P_C by [69]

$$\alpha = \alpha_0 \, P_C^n \tag{2.28}$$

Dejmek [27] has shown that n has an approximate value of 0.75 for albumin deposits. If now it is assumed that the membrane rejects the solute completely to startwith and the increase in bulk concentration with time is negligible and since $C_g >> \overline{C}(t)$, one obtains

$$V(t)\,\overline{C} - K_g A_M \, C_g \, t = \frac{A_M}{J_1(t)\,\eta\alpha_0} \int_0^{\Delta P_{gel}(t)} \frac{dP_C}{P_C^n} \tag{2.29}$$

where $\Delta P_{gel}(t)$ is the total pressure drop across the gel and from equation (2.20), neglecting the pressure drop across the diffusion layer,

$$\Delta P_{gel}(t) + \Delta P_{membrane}(t) = \Delta P$$

Thus,

$$\frac{1}{A_M}\left[\frac{dV(t)}{dt}\right] = J_1\,(t) = \frac{A_M\,(\Delta P_{gel})^{1-n}}{\alpha_0\eta\,(1-n)\cdot[V(t)\overline{C} - K_g A_M C_g t\,]} \tag{2.30}$$

For an incompressible cake, n is zero and α_0 becomes α. When the steady state is reached at time t_{ss} seconds and a volume V_{ss} of ultrafiltrate has been collected, $J_1(t)$ becomes

$$J_1 = \frac{A_M \; (\Delta P_{gel})^{1-n}}{\alpha_0 \eta \; (1-n) \; [V_{ss} \; \bar{C} - K_g A_M C_g t_{ss} \;]} \qquad (2.31)$$

For any time t, greater than t_{ss}, the curve of $V(t)$ versus t is linear and

$$[dV(t)/dt \;] = A_M J_1 \qquad (2.31\ a)$$

The volume of ultrafiltrate collected may than be represented as

$$V\ (t) = V_{ss} + A_M J_1 \; (t-t_{ss}) \qquad (2.31\ b)$$

Therefore, for time $t > t_{ss}$ equation (2.30) may be expressed as

$$J_1 = \frac{A_M \; (\Delta P_{gel})^{1-n}}{\alpha_0 \eta \; (1-n) \; [V_{ss}\bar{C} + A_M J_1 \bar{C} \; (t-t_{ss}) - K_g A_M C_g t_{ss} - K_g A_M C_g (t-t_{ss}) \;]} \qquad (2.31\ c)$$

Comparing equations (2.31 c) and (2.31), we get

$$A_M J_1 \bar{C} \; (t-t_{ss}) = K_g A_M C_g \; (t-t_{ss}) \qquad (2.32)$$

Substituting for $K_g A_M C_g$ by $A_M J_1 \bar{C}$ from (2.32) into (2.31) we get

$$J_1 = \frac{A_M \; (\Delta P_{gel})^{1-n}}{(1-n) \; \alpha_0 \eta \; [V_{ss}\bar{C} - A_M J_1 \bar{C} \; t_{ss}]} \qquad (2.33)$$

It should be noted here that equation (2.32) is very similar to equation (2.14) for the gel polarization model of Michaels which

is often expressed as [60]

$$J_1\bar{C} = K_g(C_g-\bar{C})$$

For an incompressible cake n is zero and the only unknown in equation (2.33) is α_0 since J_1, V_{ss}, $\bar{C}$, t_{ss} and ΔP_{gel} are measurable. For a compressible cake, n is an additional unknown. Thus, for a given solute, the validity of equation (2.33) may be checked if data are available on V_{ss}, t_{ss} and ΔP_{gel} for a given J_1 and $\bar{C}$. The quantity ΔP_{gel} may be obtained from a knowledge of the membrane resistance R_M, using equation (2.20). The literature on UF does not provide any information on V_{ss} and t_{ss} except for statements like - 'steady state is normally achieved in less than a minute, as shown by the invariance of UF rates over short time periods' [15]. Thus an experimental study on the initial time behaviour of UF membrane is necessary to evaluate the usefulness of equation (2.33).

It would also be of interest to consider the phenomenon of diffusion layer buildup in the pre-gel polarized region, i.e., under the conditions such that a high wall concentration of C_W (less than C_g but still considerably higher than $\bar{C}$) is reached at steady state. With a total retention membrane, such a case will lead to the following relation instead of equation (2.22)

$$\int_0^t \bar{C}(t)\, dV(t) - A_M\int_0^t K_g(t)\, [C_W(t)-\bar{C}(t)]dt = A_M\, \rho_s \int_0^{L(t)} (\bar{1}-\varepsilon)dx'' \quad (2.34)$$

where $x'' =$ Distance from the diffusion layer-bulk solution interface towards the membrane (Figure 2.1), cm.

$L(t) =$ Thickness of the diffusion layer at time t, cm.

$K_g(t) =$ Time varying mass transfer coefficient

$C_W(t) =$ Time varying wall concentration which reaches the value C_W at steady state ($t = t_{ss}$)

and other terms are as defined earlier.

For any time t beyond t_{ss}, the left hand side of equation (2.34) may be expressed as

$$V_{ss}\bar{C} + A_M J_1 \bar{C}\,(t-t_{ss}) - A_M \int_0^{t_{ss}} K_g(t)\,[C_W(t) - \bar{C}(t)]\,dt$$

$$- K_g A_M\,[C_W - \bar{C}(t)]\,(t-t_{ss})$$

$$= V_{ss}\bar{C} + A_M J_1 \bar{C}\,(t-t_{ss}) - \frac{A_M K_g C_W t_{ss}}{f} - K_g A_M C_W (t-t_{ss}) \qquad (2.35)$$

In deriving equation (2.35) it has been assumed that $\bar{C}(t) \ll C_W$ and the time dependent $K_g(t)\, C_W(t)$ product when integrated from 0 seconds to t_{ss} seconds may be expressed as a simple product of their steady state values $K_g C_W t_{ss}$ and an unknown factor (1/f). The factor f is most likely to be greater than one. Further, if the slow permeation of the solvent through the diffusion layer may still be described by Carman-Kozeny equation [23], the relationship equivalent to equation (2.33) for this

case is

$$J_1 = \frac{A_M \; (\Delta P_{gel})^{1-n}}{\alpha_0 \eta \; (1-n) \; [V_{ss} \overline{C} - \frac{A_M J_1 \overline{C} \; t_{ss}}{f} \;]} \tag{2.36}$$

where the relation equivalent of equation (2.32) is

$$A_M J_1 \; \overline{C} \; (t-t_{ss}) = K_g A_M \; C_W (t-t_{ss}) \tag{2.37}$$

Since there is an additional unknown f in equation (2.36) besides α_0 the use of equation (2.36) will be much more difficult than that of equation (2.33).

The initial time data of the present study were applied to the foregoing analysis and the details are presented in chapter 4.

CHAPTER 3

EXPERIMENTAL

3.1 Materials:

3.1.1 Suspending Media:

All solutions used in this study were prepared in appropriate buffer solutions. The buffer solutions were made up from stock solutions of 0.1 M. Citric acid and 0.2 M. Disodium Phosphate according to Table 3.1 [68]. All solutions were prepared with double distilled water.

3.1.2 Solutes:

The solutes used in the present investigation were as follows: Polyethylene glycol 20 M (PEG) was obtained from Sigma, U.S.A. Bovine Serum Albumin (Cohn Fraction V) [BSA] was obtained from V.P. Chest Research Institute, New Delhi and M/s. Centron Research Laboratories, Bombay. Ovalbumin (Wilson), Hemoglobin (EM) and Egg Albumin (Wilson) were supplied by M/s. Chempure Ltd., Bombay. All the chemicals were used as obtained. The properties [37] of these solutes are given in Table 3.2.

For initial time studies, 0.05, 0.1 and 0.5 percent solutions of the proteins were employed. For steady state studies, 0.05, 0.25 and 1.0 percent solutions of the proteins and 0.5 percent PEG solution were used. Double distilled water was used for pure water permeability studies. Teepol, a detergent, was obtained from BDH Chemicals, Bombay.

TABLE 3.1: McIlvain's Citric Acid-Phosphate Buffer

x ml. of 0.1M. Citric Acid 21.0 gms. $C_6H_8O_7.H_2O$/l.) + (100-x) ml. of 0.2M. Disodium Phosphate (35.6 gms. $Na_2HPO_4.2H_2O$/l.)

pH	3.0	4.6	4.8	6.0	6.8	8.0
x	79.45	53.25	50.70	36.85	22.75	2.75

TABLE 3.2: Properties of Solutes

Solute	BSA	Hemoglobin	OValbumin	Egg Albumin	PEG20M
Molecular weight	69,000	67,000	45,000	44,000	17,000
Isoelectric pH	4.8	6.8	4.6	4.6	-

3.1.3 Membranes:

The membranes used in these investigations, Diaflo PM 30, XM 100 A and XM 300, were obtained from Amicon Corporation, U.S.A. These membranes were of 76 mm. diameter with an effective filtration area of 33.2 cm^2. The characteristics of these membranes, namely, molecular weight cut-off, pure water permeability retention etc. are given in Table 3.3 [1,2].

3.1.4 The Ultrafiltration Cell:

The investigations reported in this study were carried out with a stirred ultrafiltration (UF) cell, so constructed as to facilitate easy dismantling and cleaning needed for the removal of any adsorbed solutes. The individual parts are shown in Figure 3.1. The bottom plate has 3.2 mm. width circular channels, connected by cross channels to a central hole, which inturn was connected to the ultrafiltrate port. The top plate houses the stirrer assembly, the baffles and the inlet ports. All the parts were fabricated with acrylic plastic to allow easy observation.

The membrane was supported by a stainless steel wire screen (80 mesh) and the cell was assembled as shown in Figure 3.2 The neoprene 'O' rings provided the sealing for leak-free operation. To maintain uniform bulk concentration and to reduce the concentration polarization effects, the solution was stirred by a nylon covered magnetic stirring bar, supported by a bearing

TABLE 3.3: Characteristics of DIAFLO Membranes

Membrane	Approximate Pore ~~Diameter~~ radius Å	Nominal Molecular Weight Cut-off	Maximum Operating Pressure psig	Maximum Operating Temperature °C	Deionized* Water Flow $ml./cm^2/min.$
PM 30	25	30,000	70	125	8-10
XM 100 A	55	100,000	70	70	0.4-1.4
XM 300	200	300,000	70	70	0.75-2.0

*Flow rates after 5 minutes at pressure, PM 30 at 55 psig and XM 100 A and XM 300 at 10 psig.

Retention Characteristics of DIAFLO Membranes*

Solute	Molecular weight	Percentage retention at pressure** indicated ( )		
		PM 30 (55)	XM 100A (10)	XM 300 (10
PEG (20M)	17,000	-	-	-
Ovalbumin	45,000	90	-	-
Hemoglobin	64,000	95	45	10
Albumin(Bovine)	67,000	95	45	10

* Values for solutions of relatively pure solutes. In some cases retentivity depends on solute concentration and pressure.

** Average value after 10-30 minutes continuous ultrafiltration in stirred cells.

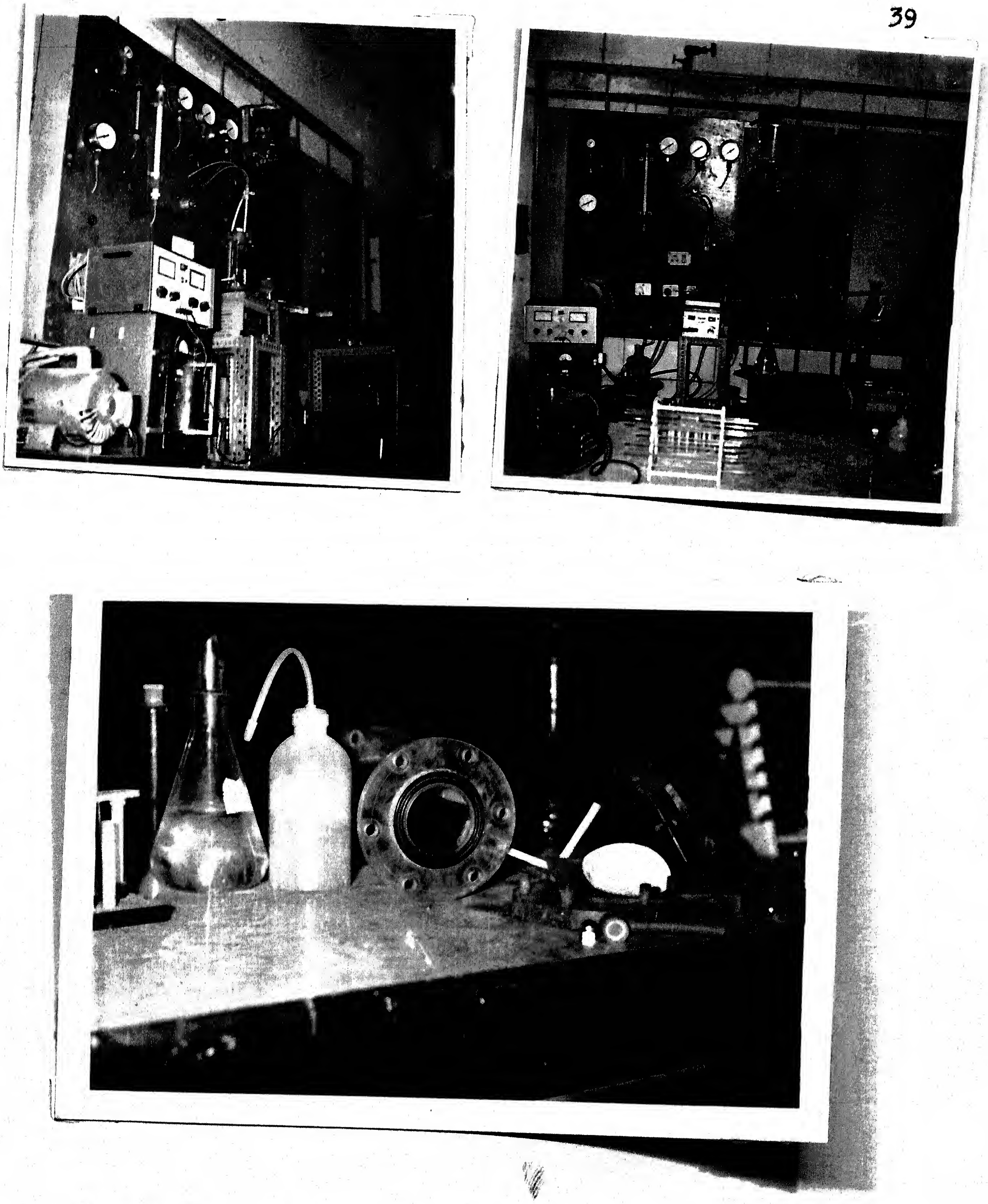


Figure 3.1 The Experimental Set up and the Individual Parts of the Ultrafiltration Cell

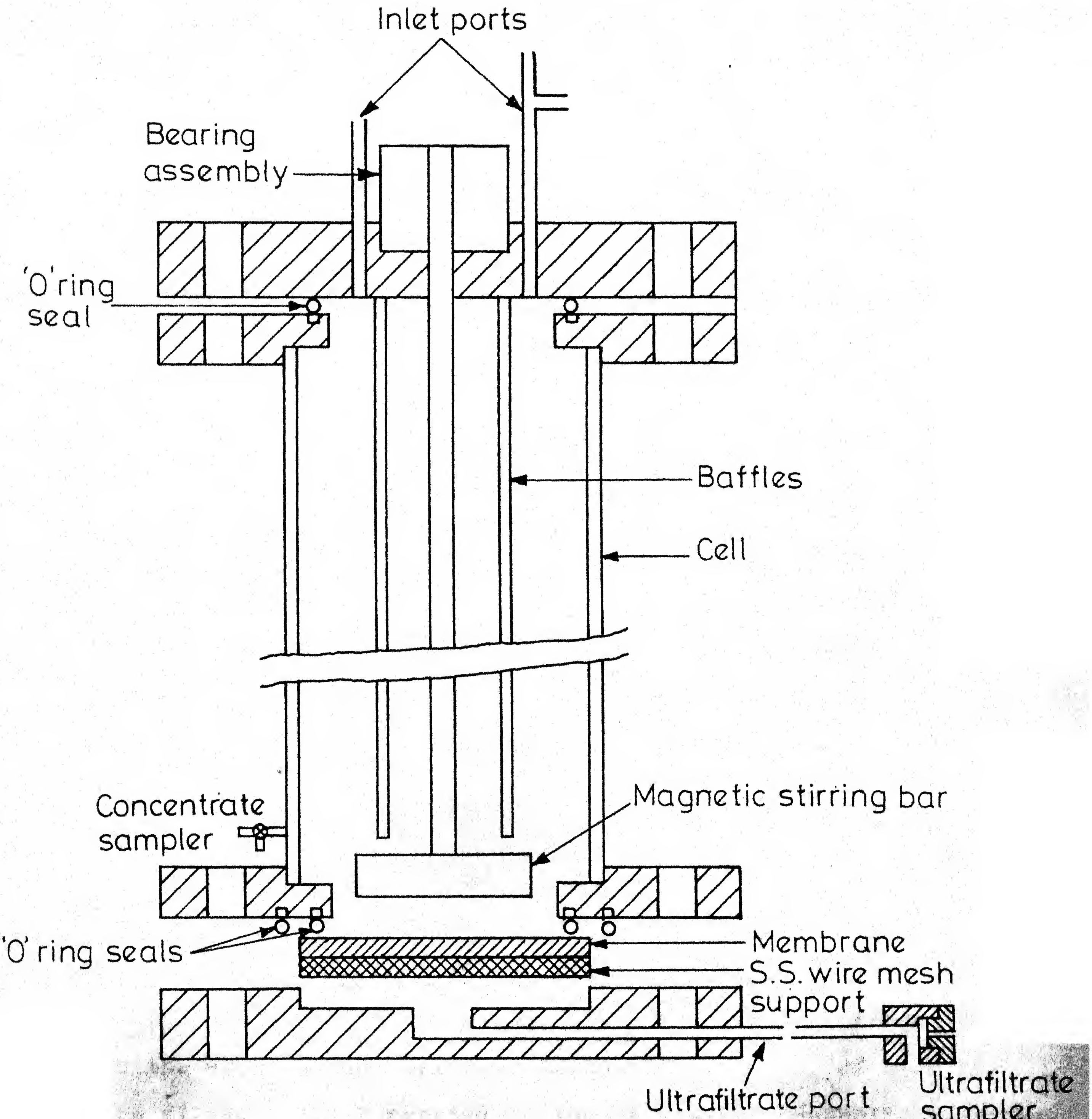


Fig. 3·2 – Stirred ultrafiltration cell assembly.

assembly from the top plate and located 6.35 mm. above the membrane surface. Baffles were used to further improve the mixing.

3.1.5 The Ultrafiltration System:

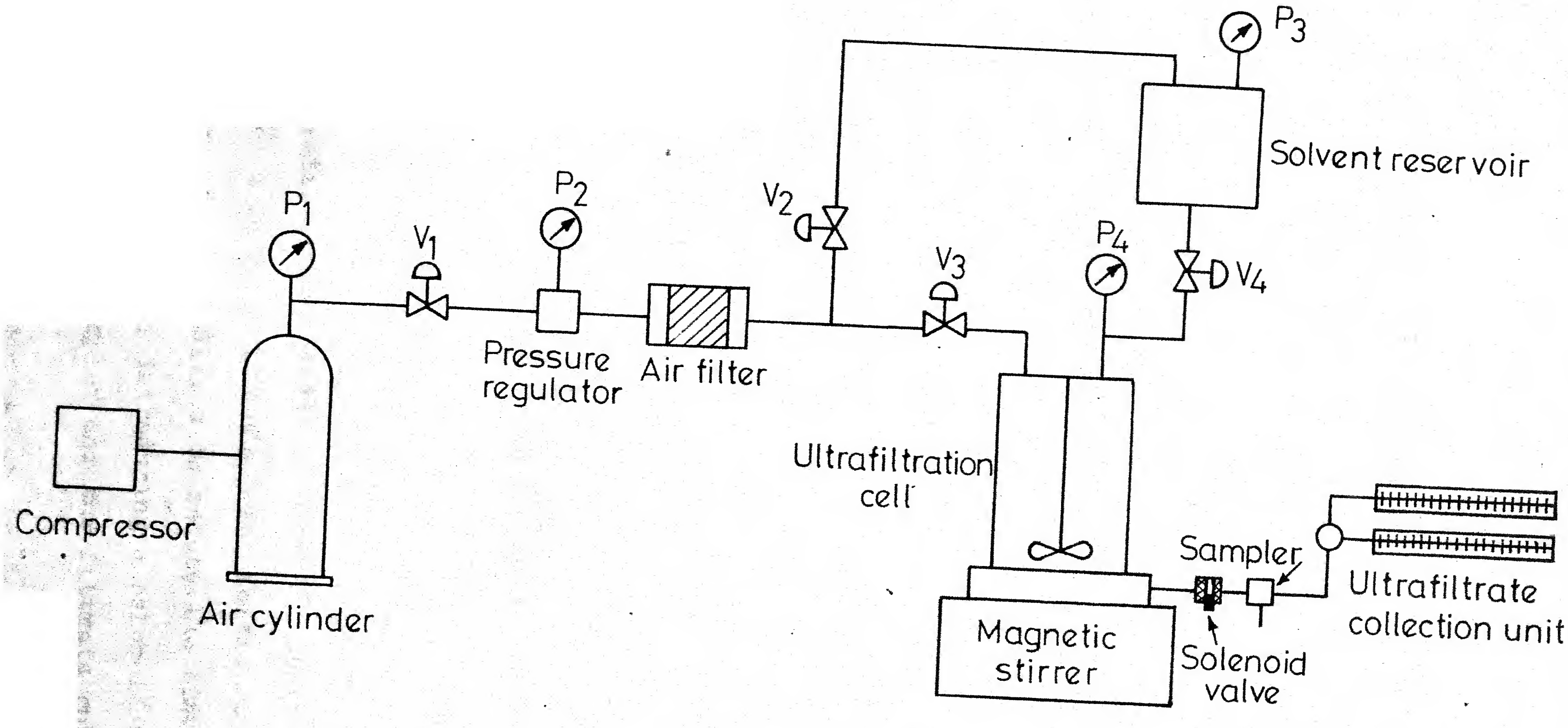
A schematic flow diagram of the experimental unit is shown in Figure 3.3. It consists of an oilless compressor, a cylinder for air storage, a pressure regulator, an air filter, a solvent reservoir, pressure gauges, valves, UF cell, UF sampler and an ultrafiltrate collection unit. All connections were made with 6.35 mm. nylon pressure tubings and fittings. The connections were made in such a way that the cell could be easily disconnected from the rest of the system.

The ultrafiltrate collection unit consisted of two modified graduated burettes, positioned slightly inclined ($\simeq 10^0$) and interconnected by a 3-way glass stopcock.

3.2 Methods:

3.2.1 Experimental Procedure:

Prior to making any run, the air cylinder was filled with compressed air, and the solvent reservoir was filled with the appropriate buffer solution. The cell was then assembled with the membrane in position, filled with 250 ml. of solution to be filtered and connected to the UF system. Magnetic stirring was initiated next. Valve V_4 was opened to flush the air from



P_1, P_2, P_3, P_4 - Pressure gauges
V_1, V_2, V_3, V_4 - Valves

Fig. 3.3 - Schematic diagram of the experimental system for ultrafiltration studies.

the connecting assembly and then closed. Valves V_1 and V_2 were opened and the solution in the reservoir was pressurized to the operating pressure. Valve V_2 was closed at this time and valve V_3 opened and the cell solution was pressurized. When the desired pressure was reached in the cell, V_3 was closed and V_2 and V_4 opened quickly. As the solution was discharged by ultrafiltration from the cell, solvent was replaced from the reservoir. The same starting pressure in both the cell and the reservoir minimized any volume change that can occur in the cell during operation.

The time of ultrafiltration was measured from the instant of cell pressurization. The void volume of the system, from the bottom of the membrane to the starting point of the filtrate collection burette, was initially filled with double distilled water to avoid the time lag in the measurement of the rate of filtration [14]. All the runs were taken at room temperature which was in the range of 25-30°C. The temperature of the cell solution was measured and found to be constant during the run.

The procedure outlined above was used for steady state ultrafiltration studies, where the desired cell pressure was reached in 20-30 seconds. For initial time studies, this procedure was modified to reduce the time required for pressurization by introducing a solenoid valve between the ultrafiltrate sampler and the filtrate collection unit. This

valve was kept closed when the cell was pressurized and opened when the desired pressure was reached, which was within 10 seconds. The time of filtration in this case was measured from the instant the solenoid valve was opened.

The burette reading corresponding to the meniscus of the ultrafiltrate was noted at regular time intervals. Samples of the retentate and the ultrafiltrate were also taken at regular intervals. The steady state experiments were conducted for 1 hour with burette reading noted every minute. Samples were taken at 1,5,10,20,30,45 and 60 minutes from the start. The initial time studies were carried out for 15 minutes with burette reading noted every 15 seconds upto 5 minutes and after every 30 seconds thereafter. Samples were taken at 1,3,5,10 and 15 minutes from the beginning.

At the end of the run, the stirring was stopped, valves V_2 and V_4 were closed and the cell solution was discharged and the pressure was released slowly. The cell was then disconnected from the system, disassembled and all the parts were cleaned with tap water. The membrane was cleaned by the procedure described in section 3.2.6. The ultrafiltrate was removed from the collection unit and the whole collection assembly including the sampler were cleaned with tap water. Reproducibility was checked for some experiments early in the study with the same membrane and found to be reasonably good.

3.2.2 Flux Measurement:

The ultrafiltration flux was calculated from the rate of filtration given by the slope of the plot of volume of ultrafiltrate collected versus time of filtration. Since the rate of filtration changes with time continuously, due to concentration polarization, this method of measuring the rate gives a better estimate of the flux than the conventional methods.

3.2.3 Sampling:

Concentrate samples were taken through a sampling valve located above the membrane, near the stirrer.

The ultrafiltrate sampler for the steady state studies was an ordinary 3-way glass stopcock. Since the rate of filtration was very small, the time for sampling by this method was very high. Hence for initial time studies, sampling was done with a syringe through a sampling block shown in Figure 3.2, connected directly to the ultrafiltrate port. Sampling, by this method took only 20-30 seconds. The sample volumes for steady state and initial time studies were 2.5 ml. and 1.0 ml. respectively. This sample volume was taken into account while measuring the volume of filtrate. The samples were diluted, where necessary, for concentration measurements.

3.2.4 Concentration Measurements:

Concentration of the polyethylene glycol samples were

measured with a differential refractometer (Brice-Phoenix, Model BP-2000-V, U.S.A.). The calibration plot for the differential refractometer is given in Figure 3.4.

Concentrations of the protein samples were measured by two different methods, depending on the concentrations, using a spectrophotometer (Bausch and Lomb Model 33-31-72). For very dilute samples (0-200 µg/ml.), a sensitive Lowry's method [53], and for relatively concentrated samples (0.25 mg.-2.0 mg./ml.) a modified Biuret method [18] were used.

<u>Lowry's Method</u>:

Reagent A: 2 percent Sodium Carbonate in 0.1 percent Sodium Hydroxide.

Reagent B: 0.5 percent Copper Sulphate ($CuSO_4.5H_2O$) in 1 percent Potassium Tartarate.

Reagent C: Prepared on the day of use by mixing 50 ml. of Reagent A and 1 ml. of Reagent B.

Reagent D: Folin-Ciocalteau reagent [Prepared according to Litwack [52]].

A volume of 1 ml. of the sample, whose concentration was to be determined, was mixed with 5 ml. of alkaline solution (Reagent C) and allowed to stand for 10 minutes at room temperature. Then 0.5 ml. of Folin's reagent was added to it with mixing and the optical density (O.D) was taken at 660 nm after 30 minutes.

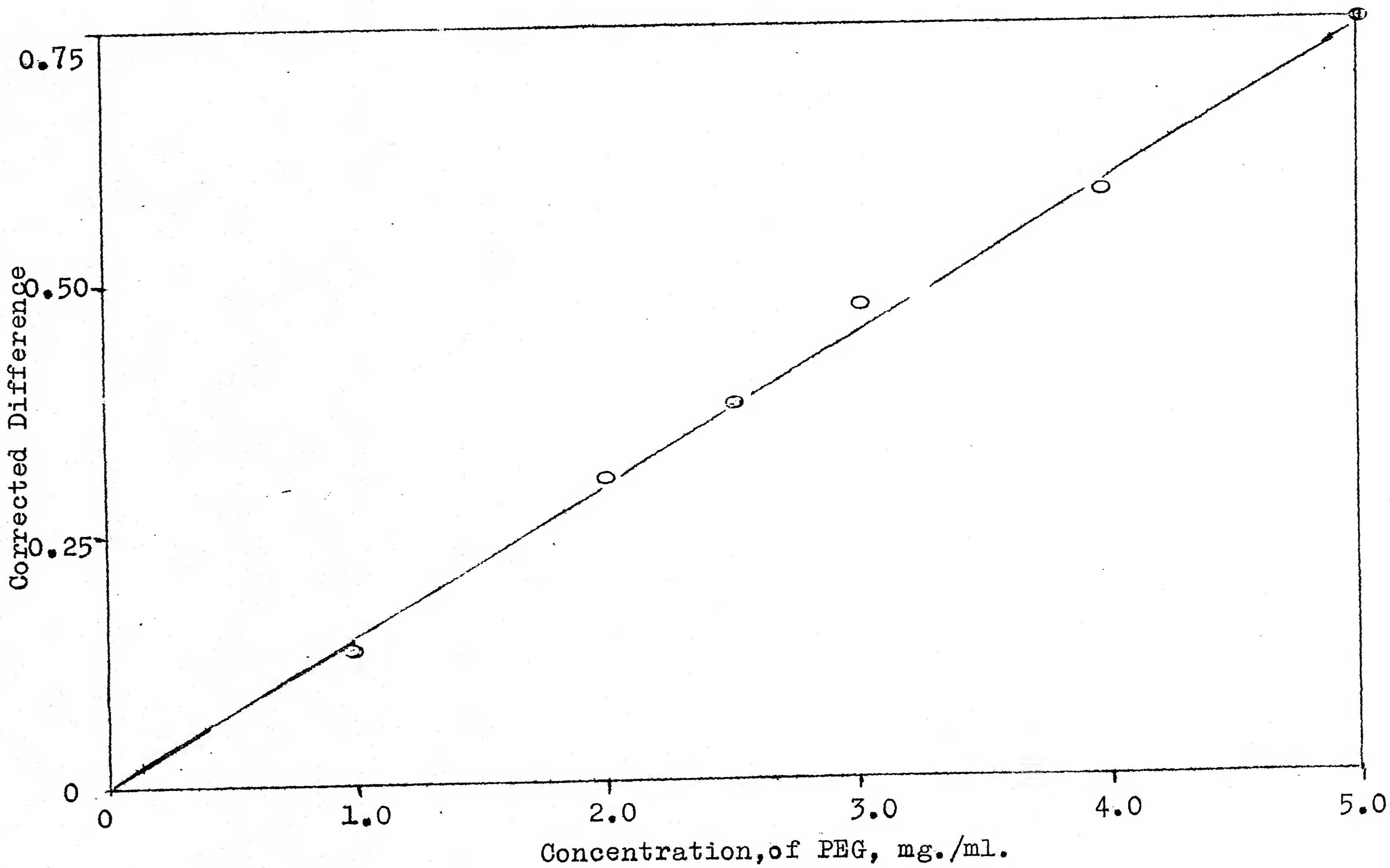


Figure 3.4 Calibration Curve for PEG Concentration Measurement

The concentration was read from the calibration curve shown in Figure 3.5.

Biuret Method:

Biuret reagent was prepared by the method of Bailey[3] A volume of 2.5 ml. of Biuret reagent was added to 2.5 ml. of sample solution. The mixture was allowed to stand at room temperature and the O.D. was measured at 540 nm after 30 minutes. The concentration was read from the calibration curve shown in Figure 3.6.

3.2.5 Solute Retention Measurement:

The solute retentions were calculated from measured values of concentration of ultrafiltrate at different times and the bulk solute concentration using equation 2.9.

3.2.6 Membrane Cleaning:

When a membrane is used for a number of experiments it has to be cleaned after each use, since there will be some clogging and adsorption of solutes on the surface. Various methods for membrane cleaning have been reported. These methods include use of 0.1N Sodium Hydroxide [51], detergents [2] and enzyme solutions [31,32,36]. For severely clogged membranes, back flushing has been used [25].

The following procedure was used in the present study. At the end of the run, the membrane was removed from the cell,

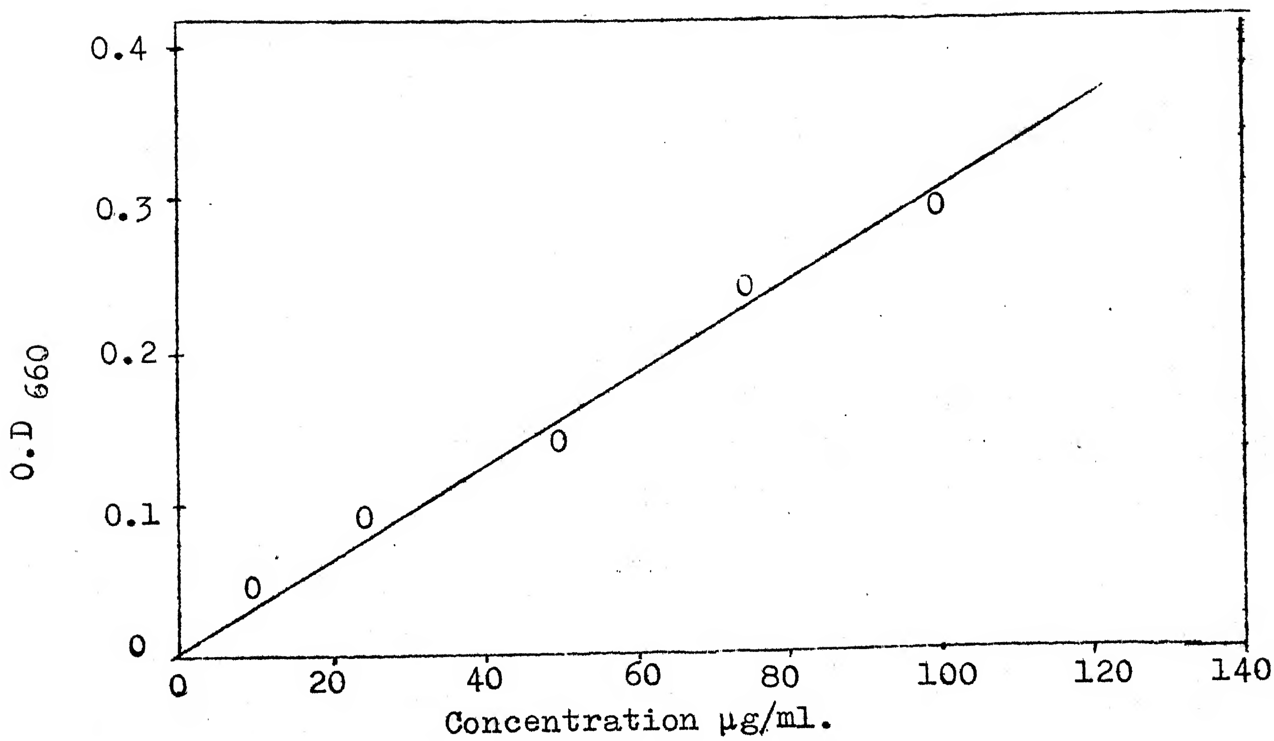


Figure 3.5 Calibration Curve for Protein Concentration Measurement (Lowry's Method)

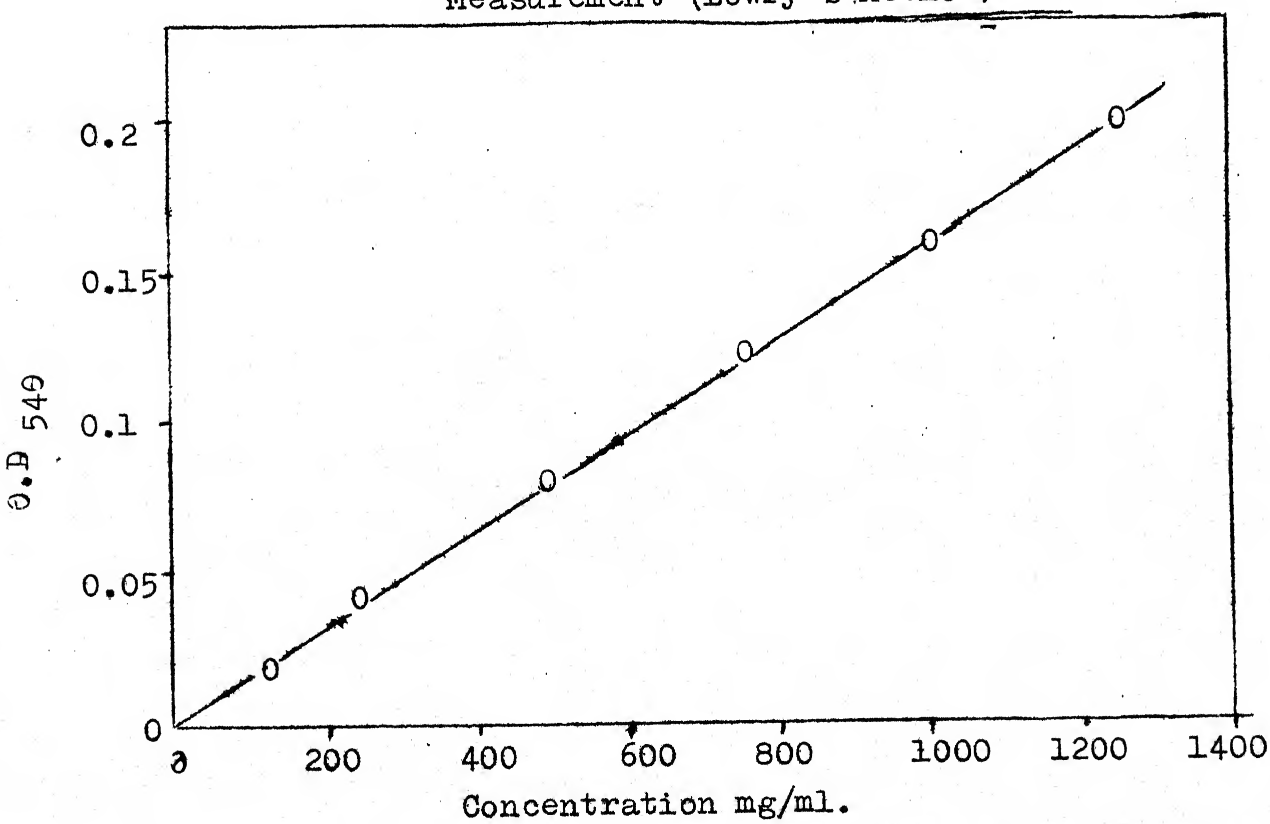


Figure 3.6 Calibration Curve for Protein Concentration Measurement (Biuret Method)

washed with tap water and kept in 0.1N NaOH solution for 10 to 15 minutes. It was then cleaned with tap water again, placed in the cell and double distilled water was passed through at the the same pressure to which the membrane was exposed in the previous run, for 15 minutes. The membrane was again removed, cleaned with0.1NNaOH and double distilled water was passed through it at 10 psig and the filtration rate was measured. This procedure was followed till the original membrane performance with distilled water at 10 psig was restored. It was found that the rate of filtration in the first cleaning step was lower than the original rate indicating clogging of the membrane.

It is worthwhile to note here Dejmek's [27] observation that there is no precise indication of when a membrane is satisfactorily cleaned. He further observed that even if the original water permeability is restored, the cleaned membrane some times experiences a faster flux decline than a virgin one.

CHAPTER 4

RESULTS AND DISCUSSION

The results of the investigations carried out in the present study are reported and discussed in this chapter under two categories. The results of the initial time studies on protein ultrafiltration (UF) are discussed in the first part while the second part deals with the steady state UF performance of the membranes studied.

4.1 Pure Water Filtration:

The results of pure water filtration studies are shown in Figure 4.1 as a function of time for various UF membranes. The experiments were conducted for durations much longer than shown in Figure 4.1. However, the general trend shown in this figure was maintained over these long periods. Even though the rate of filtration as shown in this figure is essentially constant, there is a slight decline in the rate as time progresses. This could be due to membrane compaction as well as deposition on the membrane of trace amounts of suspended solids present in the water. The latter seems to be the main factor as a very thin slime layer was detectable over the membrane surface at the end of each experiment lasting for more than two hours. This is further confirmed by the fact that the original performance of each membrane was restored after empolying the cleaning procedure described in Chapter 3.

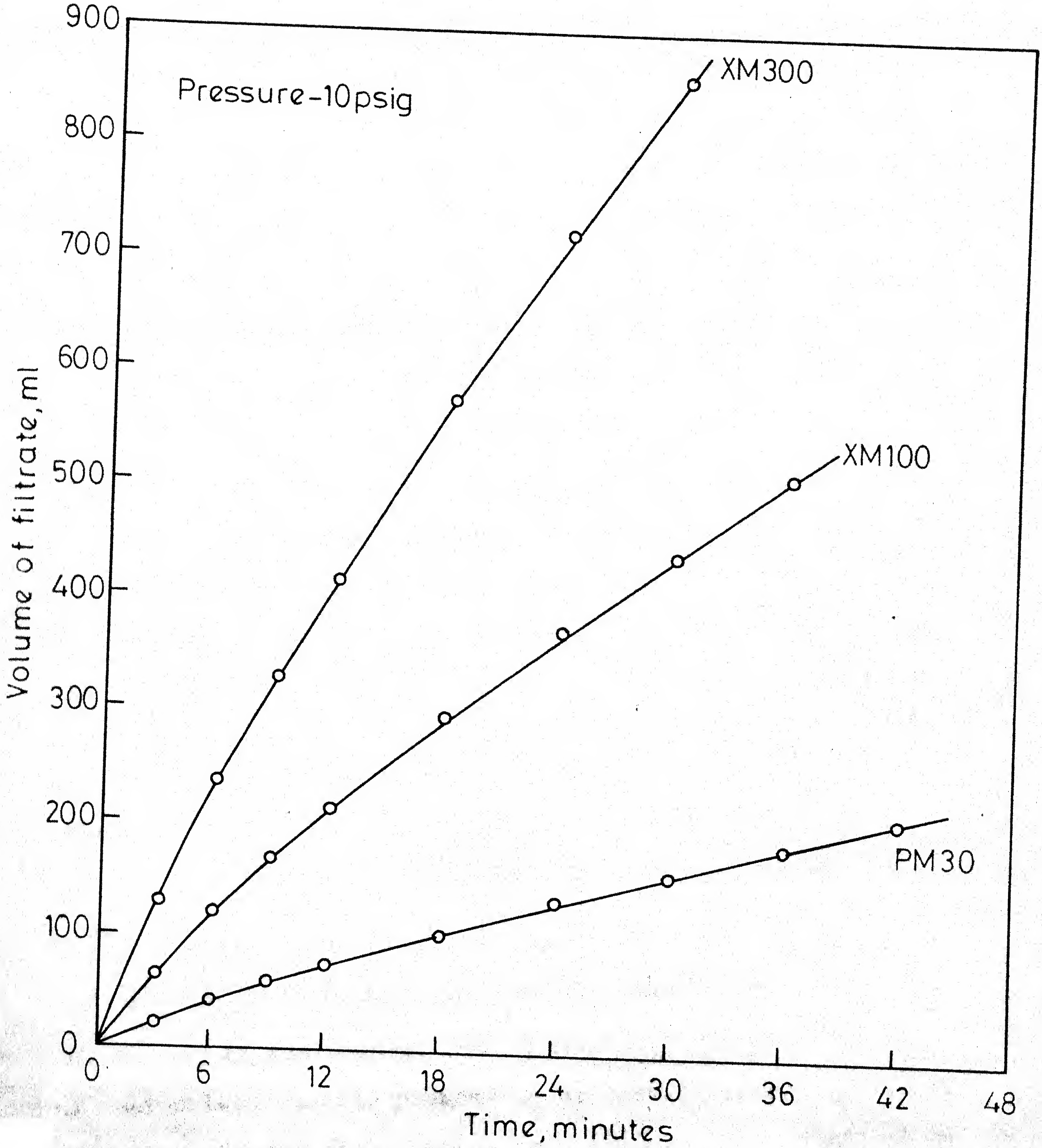


Fig. 4.1 - Pure water filtration through ultrafiltration membranes.

Figure 4.2(a) shows the initial time behaviour of pure water filtration rate for a PM 30 membrane at various applied pressures. It can be observed that the rate is constant over the whole period and that this steady rate is reached within a very short period of 10-15 seconds at all the pressures investigated. This would indicate that the process of short term membrane compaction is complete within a short period at the beginning. The significance of this compaction period will be discussed in the next section.

The pure water fluxes are plotted as a function of pressure in Figure 4.2(b). It is interesting to note in this figure that, contrary to the general notion, there is a non-linearity in the flux - ΔP curve for pure water filtration. Michaels [58] has pointed out that for diffusive type cellulose acetate desalination membranes also, water flux is not quite linear in $(\Delta P - \Delta\pi)$, due to membrane compression at high pressure. Copas and Middleman [21] have also reported non-linear flux versus ΔP behaviour for water with cellulosic (HFA-300) membranes.

4.2 Protein Ultrafiltration: Initial Time Studies:

It was pointed out in Chapter 2 that, in the UF of macromolecules, the phenomenon of concentration polarization adversely affects the membrane performance and a steady state is eventually reached, at which, the UF performance is considerably

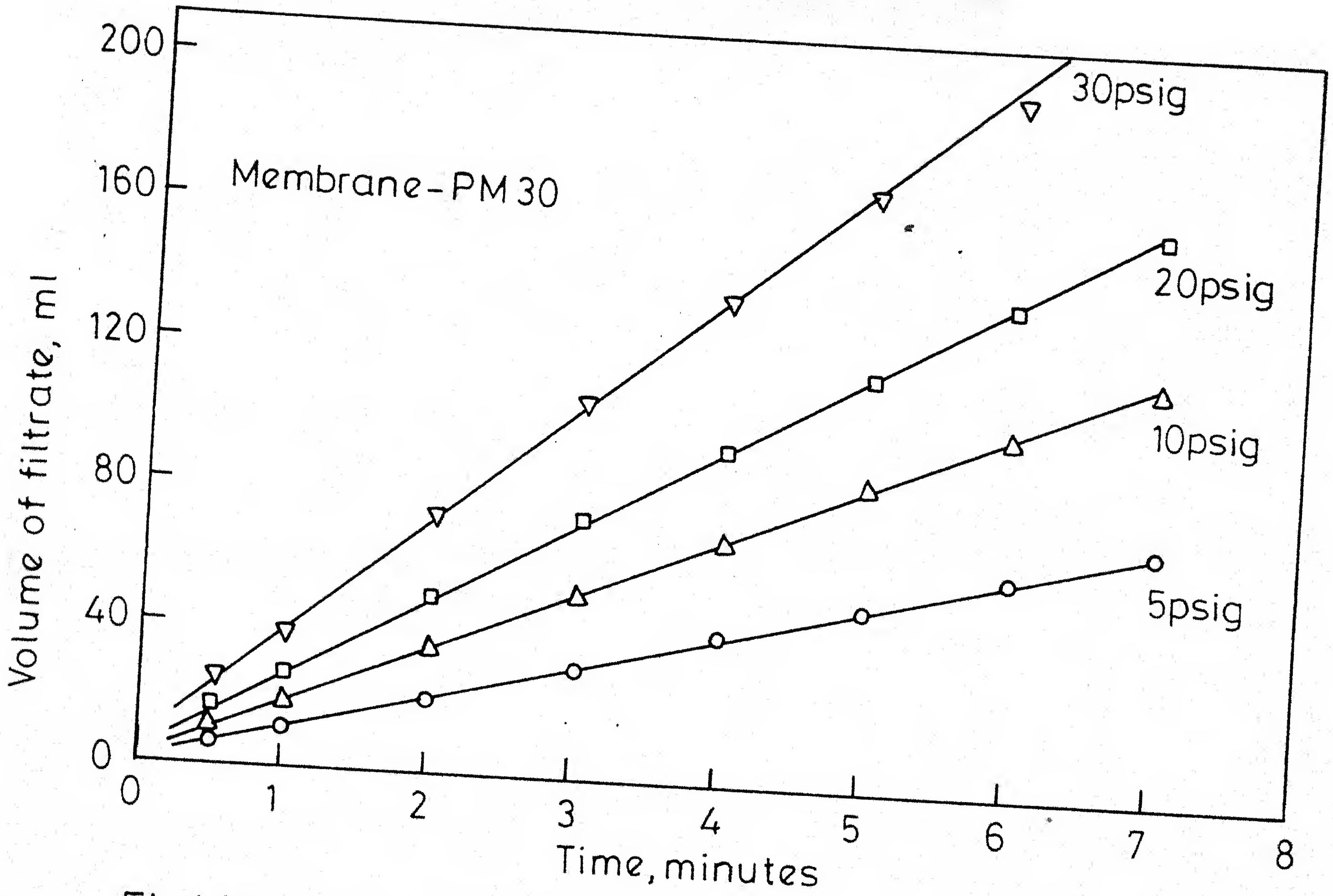


Fig.4.2a – Pure water filtration results. (initial time).

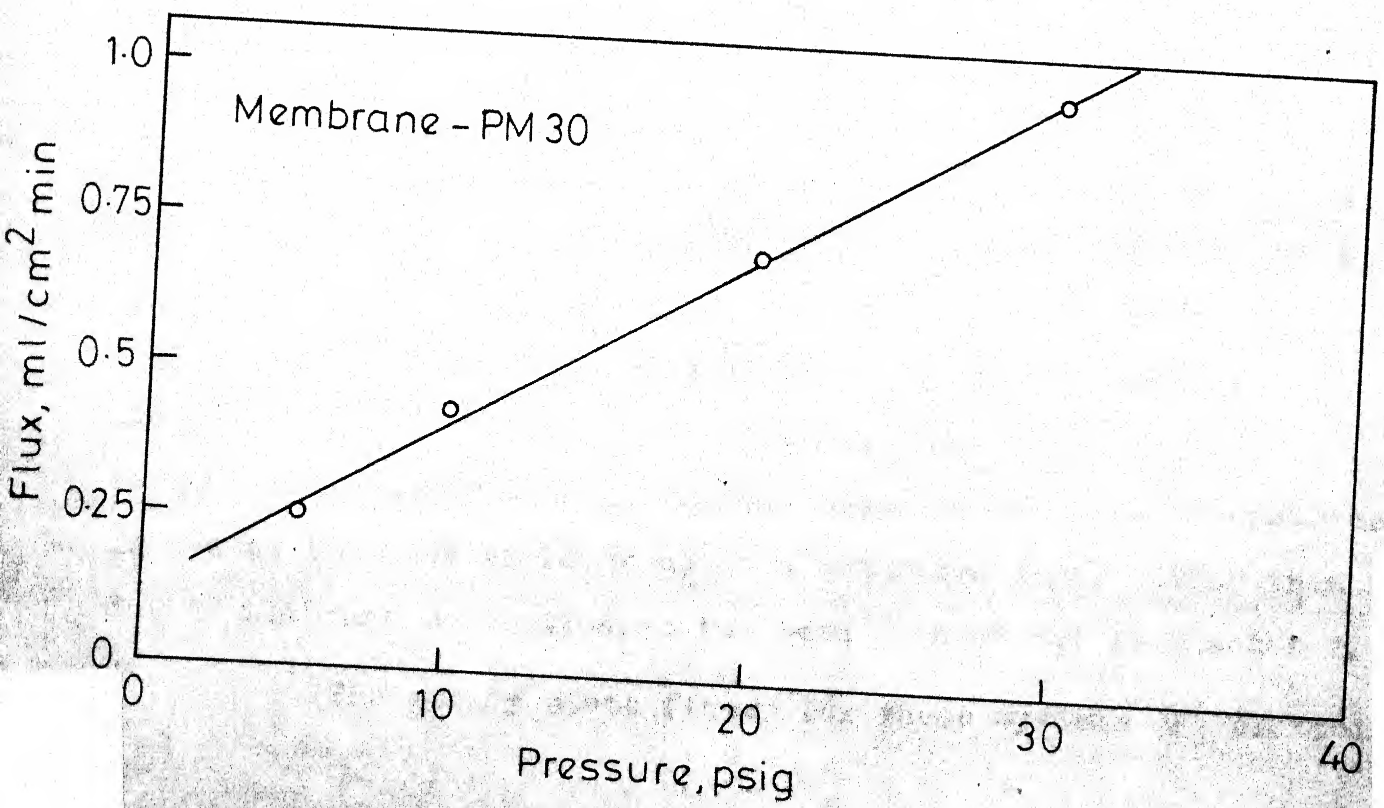


Fig.4.2b – Flux–pressure relationship with pure water.

different from that of the membrane, when only pure water is used. Experiments were conducted to study the UF performance in the early phase of the polarization process leading to a steady state and the effect of various parameters on this performance. The results are presented and discussed in this section. Reproducibility of the experimental results was checked for a few runs early in the study with the same membrane and the agreement was found to be fairly satisfactory.

4.2.1 Effect of Pressure:

The results of initial time UF experiments with 0.05 percent BSA and Ovalbumin solutions are presented in Figure 4.3. As can be observed from the variation of the slopes of the curves, the rate of filtration decreases with time and after a certain time τ_{ssp}, reaches a steady value. Comparison of this time, τ_{ssp}, with the time required to reach steady sate with pure water, τ_{ssw}, discussed in section 4.1, indicates that $\tau_{ssp} \gg \tau_{ssw}$. Further, the sharp decrease in the rate of filtration for protein solutions as compared with the filtration rates for pure water, clearly indicates that the large time required to reach steady state in the case of proteins is due to the slow building up of a polarized layer rather than due to membrane compaction, as has been pointed out in Chapter 2.

The steady state fluxes for these systems are plotted

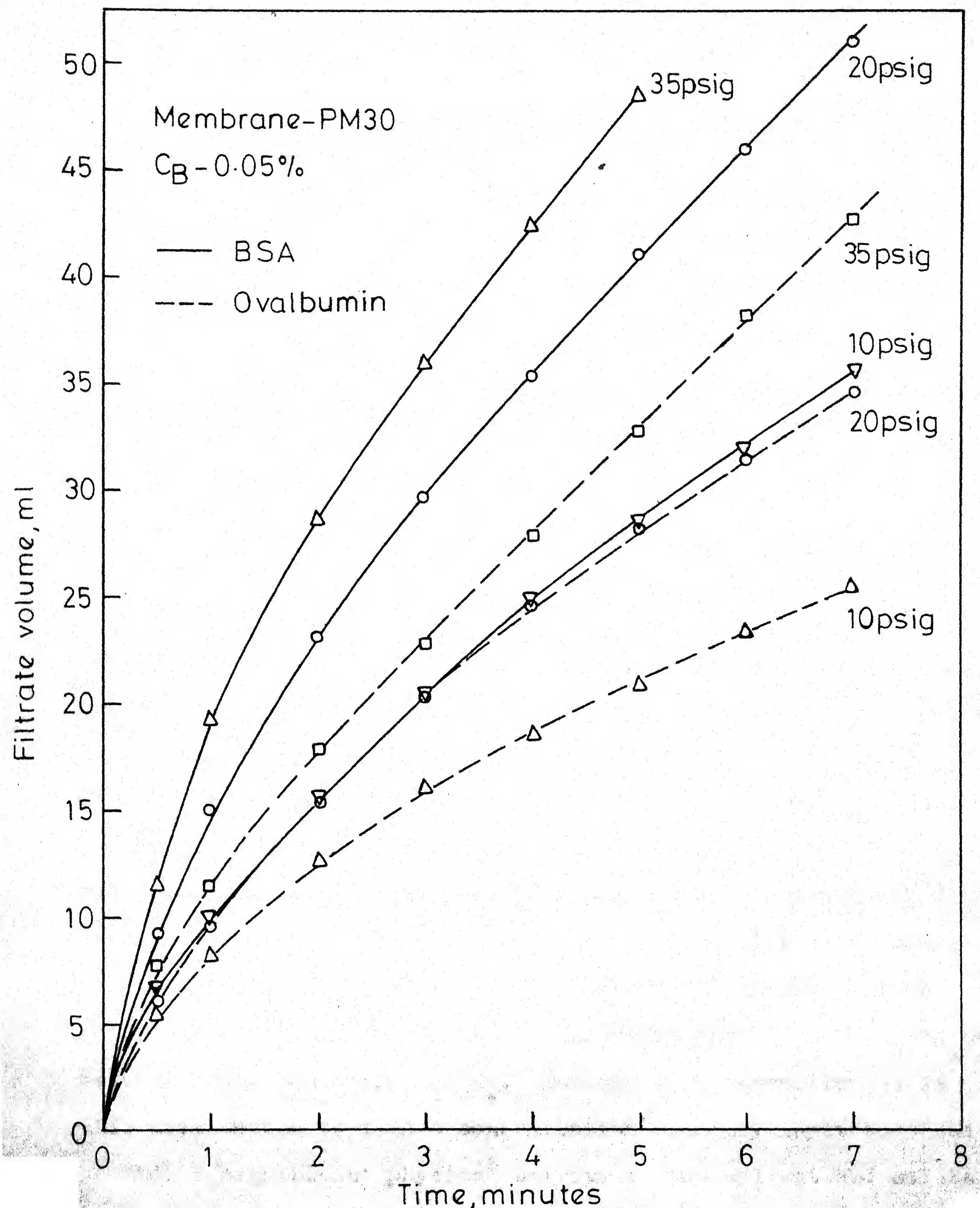


Fig. 4.3 – Ultrafiltration results at different pressures for proteins.

as a function of pressure in Figure 4.4. It may be noticed that the flux increases as the pressure increases. However, the rate of increase becomes smaller at higher pressures and the fluxes seem to reach a limiting value at the highest pressure used.

According to the gel-polarization model of Michaels [15], the UF flux of macromolecular solutions should be independent of applied pressure. An increase in pressure while increasing the initial UF rate, does not aid back transport rate of the solute and results merely in a thicker gel layer which, then reduces the flux down to its original value where the convective solute flux toward the membrane can be balanced by the rate of back diffusion of solute species. It has been observed by others [5,15,64] that this pressure independent flux is achieved only at high pressures, particularly with dilute solutions, and at low pressures significant deviations occur. It has been hypothesized [15] that for low enough pressures, gel polarized model is not valid. Rather, the fluxes are controlled by a region called 'the pre-gel polarization region', in which the concentration polarization modulus (C_W/C_B) is low enough for the wall concentration C_W to be below the gel concentration C_g. But the wall concentration is also high enough to form a concentration boundary layer that can provide a significant physical barrier to the solvent and solute transport. The steady UF flux is determined by a balance between the rate of convective solute transport towards the membrane

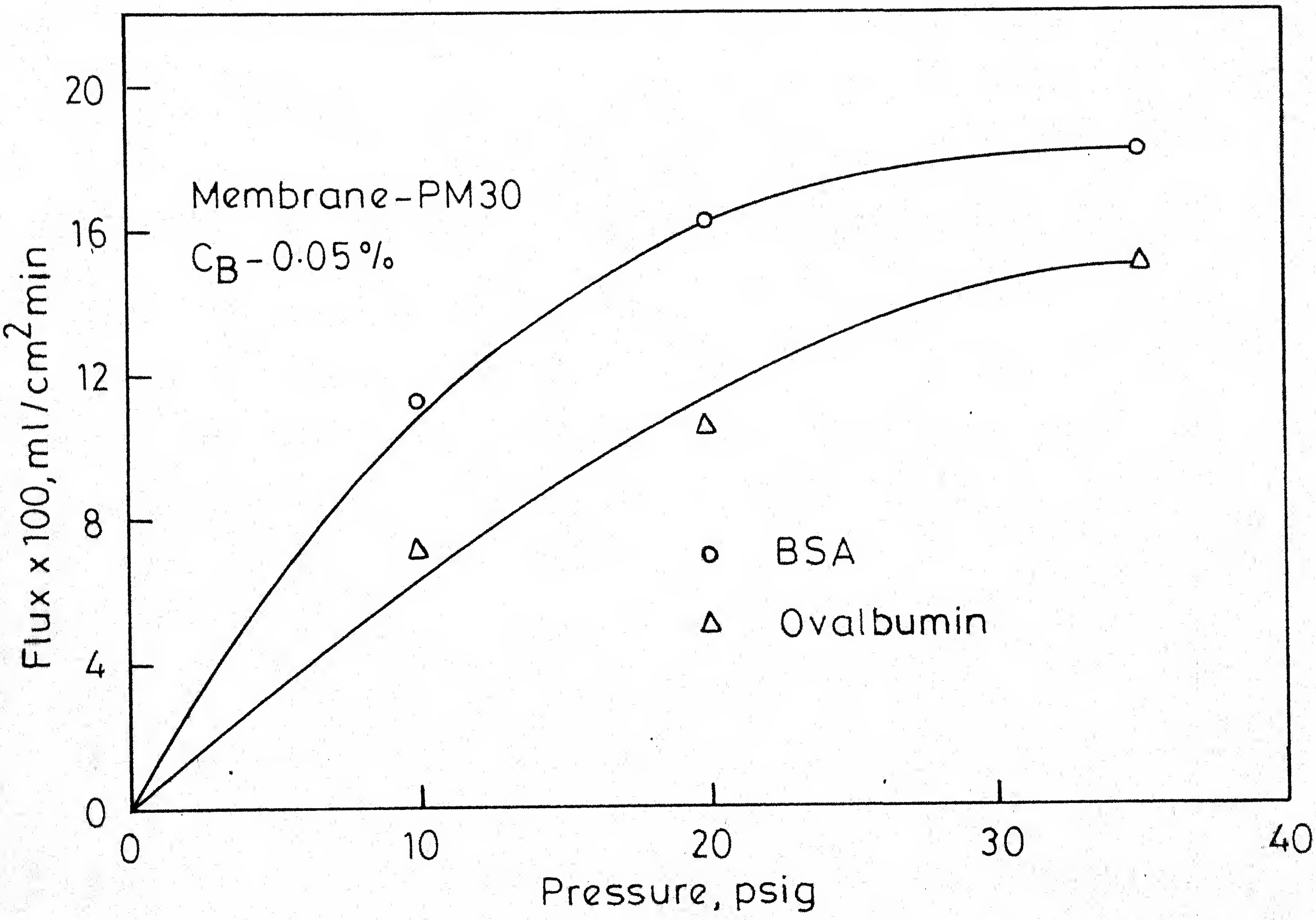


Fig. 4.4 - Effect of pressure on ultrafiltration flux.

surface and the rate of transport of the solute to the bulk solution by back diffusion. According to this hypothesis, as the pressure is increased, more solute is brought to the membrane surface (due to increased initial UF rate) thereby increasing C_W, which increases the back transport of the solute into the bulk, resulting in a net increase in the flux. But, as the pressure is increased further, C_W approaches C_g, and no further increase in back diffusion can take place and the flux henceforth remains constant. This hypothesis is supported, to some degree, by the concentration dependence on pressure effect, as will be shown later.

The solute retention data are plotted as a function of time in Figure 4.5 for various applied pressures. This figure shows that the solute retention increases with time and reaches a a steady value in about 10 minutes. The data further shows that the solute retention decreases with increasing pressure as the pre-gel polarization gets converted to the gel polarized layer. This behaviour coupled with the fact thata polarized layer is formed over the membrane surface indicates that the polarized layer not only alters the flux but also the retention characteristics of the membrane. The data indicates that the polarized layer has a tighter structure when compared with the primary membrane. This behaviour has been confirmed by other investigators also. Shah et al. [65], in their study of enzymic hydrolysis of starch

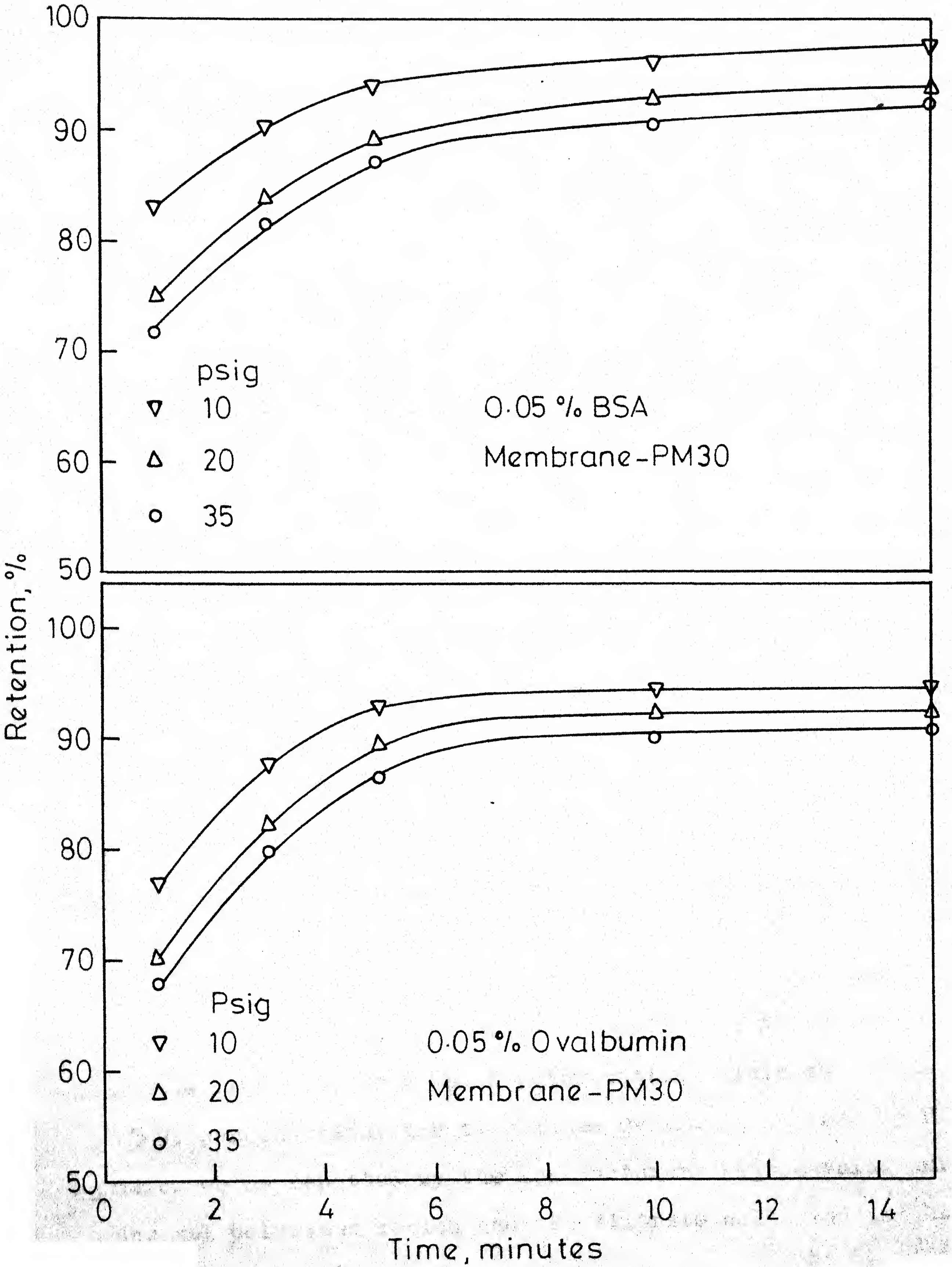


Fig. 4·5 -Effect of pressure on retention.

in membrane reactor, have observed rejection increasing with time and complete rejection of starch, limit dextrin and enzyme. They attribute this enhanced rejection to the formation of a gel layer which eventually controls the retention characteristics of the system. Belluci et al.[8] have also reported, in a study on protein UF, increasing retention with time at various applied pressures. Dorson et al. [29], in a study on UF of tracer molecules through deposited protein layers, found that the protein layer offered significant resistance to the passage of tracer molecules even with a minimal deposit. They also found that the molecular weight of tracer molecule first exibiting zero rejection was markedly reduced by the deposited protein layer, which clearly shows that the deposited layer has a tighter structure than the primary membrane. Enhanced rejection by gel layer has been reported also by Sinskey et al. [67] and Wang et al. [17].

According to the gel-polarization model, if the feed solution contains a single solute and if the primary membrane is essentially impermeable to that solute, the formation of a gel layer of that solute (while it may markedly reduce the flux) will not influence the solute retention [15]; the filtrate will be solute free with or without polarization. This shows that the >95 percent retention of solutes Ovalbumin and BSA by PM 30 membrane as reported by the manufacturers [2] is valid only in the gel polarized region and the filtrate collected in the

initial periods of such membranes needs careful analysis, if not total rejection.

Another evidence for the partial permeability of this membrane PM-30 to the solutes Ovalbumin and BSA is the decrease in solute retention with an increase in pressure. If the primary membrane is partially permeable to the solute, then the retention will depend upon the properties of the gel layer. When UF is conducted at low pressures with quite dilute solutions, the polarized layer will be viscous but still the solute molecules within this layer are relatively mobile. Further, the locally high solute conentration near the membrane surface increases the solute flux through the primary membrane, thereby reducing the retention. As pointed out earlier, in the pre-gel polarization region, increasing pressure, increases the concentration polarization modulus (and hence C_W) so that the retention decreases. Similar pressure effects on retention were observed by Baker[5] in the UF of dextrans and by Michaels et al. [60] in the fractionation of defatted milk whey and a similar explanation was also offered by them. It must be recognized, however, that increasing pressure leading to higher pore flux and therefore higher shear rates in the pores will also effectively uncoil the linear macromolecules like dextrans and lead to lower retention [5]. A decrease in retention may also result from elastic distortion of the membrane leading to an increase in pore size [58].

Belluci et al.[8] have also reported decreasing retention with pressure in the initial transient phase.

The transient behaviour of the solute retention and solvent flux in membrane UF, as discussed above, points out the difficulties of characterising the true membrane properties in protein UF due to the gel polarization phenomenon. For proper characterization of UF membranes with respect to macromolecules which are likely to be even slightly permeable, unsteady state measurements are thus likely to yield better characterization of the membranes.

4.2.2 Time to Reach Steady State:

The time taken to reach a steady state is defined as the time at which the curve of filtrate volume versus time becomes a straight line of constant slope. Estimates of this time for various pressures and concentrations are presented in Table 4.1 for both the solutes.

Even though the formation of a gel polarized boundary layer, which drastically affects the membrane performance in macromolecular UF has been known for sometime, not many attempts to study the formation and nature of the gel layer have been reported in the literature. It has generally been accepted that the gel layer is formed within a very short time period and most of the UF studies, reported in the literature, have been carried

TABLE 4.1 TIME TO ATTAIN STEADY STATE

Membrane	Applied Pressure psig	Time to Reach Steady State, seconds						
		Ovalbumin, percent			BSA, percent			
		0.05	0.5	0.05 unstirred	0.05	0.1	0.5	0.05 unstirred
PM 30	10	174	54		147	66	33	
	20	234	84	96	204	111	105	141
	35	120	69		150		60	
XM100A	10	183	69		156	60	48	
	20	240	105	192	210	165	87	156
	35	165	78		180		66	
XM300	10	198	78		186	96	60	
	20	261	114	176	234	174	90	150
	35	187	90		201		71	

out in the gel polarized region. The few studies on gel layer that have been reported [24,25,27,29] use the method in which the gel layer is first deposited on the membrane and then studied by passing the solvent or other solutes through it. While carrying out one such study, Dejnek [27] estimated, theoretically,

the time to reach steady state to be less than one second. However, as shown in Table 4.1, even with the unstirred system in the present study much higher value (about 100 seconds) was obtained for the time to reach a steady state in the UF flux.

Another interesting phenomenon that can be observed from Table 4.1 is that the time to reach steady state increases with pressure at low pressures but decreases at high pressures. This may be explained, qualitatively, in the following manner: At low pressures, as the pressure is increased, more solute is brought to the membrane surface and C_W, presumably increases, thereby increasing the back transport as well as the solute transport through the membrane (Retention is decreased). The net result of this will be a reduction in the rate of accumulation of protein on the membrane surface and consequently, the time to reach steady state will increase. But, as the pressure is increased further, while the forward convective transport increases, the back transport reaches a limiting value, as C_W approaches C_g and the decrease in retention also is reduced. This leads to a relatively quicker attainment of the steady state at the highest pressures.

4.2.3 Effect of Concentration:

To study the effect of solute concentration on UF performance experiments were conducted also with 0.5 percent

Ovalbumin and 0.1 percent and 0.5 percent BSA solutions. The results presented in Figure 4.6, indicate the same trend as those for dilute solutions with the exception that the fluxes as well as the time required to achieve a steady state are much smaller.

The concentration polarization model predicts, according to equation (2.12), the steady state UF flux to be a linear function of the logarithm of the bulk concentration. The results of the present investigation agree with this predicted behaviour as is shown in Figure 4.7. Similar flux dependence onconcentration has been reported by many workers [36,51,59,63].

Two other aspects are also noticeable in Figure 4.7. First, the slope of the plot changes with pressure and secondly, the intercept at the concentration axis varies with pressure. If the UF is carried out in the gel polarized region, then this intercept will not vary with pressure, since it must be equal to C_g. But in the pre-gel polarization region, in which bulk of the present investigations were conducted, C_W changes with pressure as pointed out earlier and hence this behaviour of flux versus C_B could be justified. In fact, the intercepts for Ovalbumin at 20 psig and 35 psig are quite close to each other. As shown in Figure 4.8, these are almost in the gel-polarized region which is not true for the BSA runs except at 35 psig.

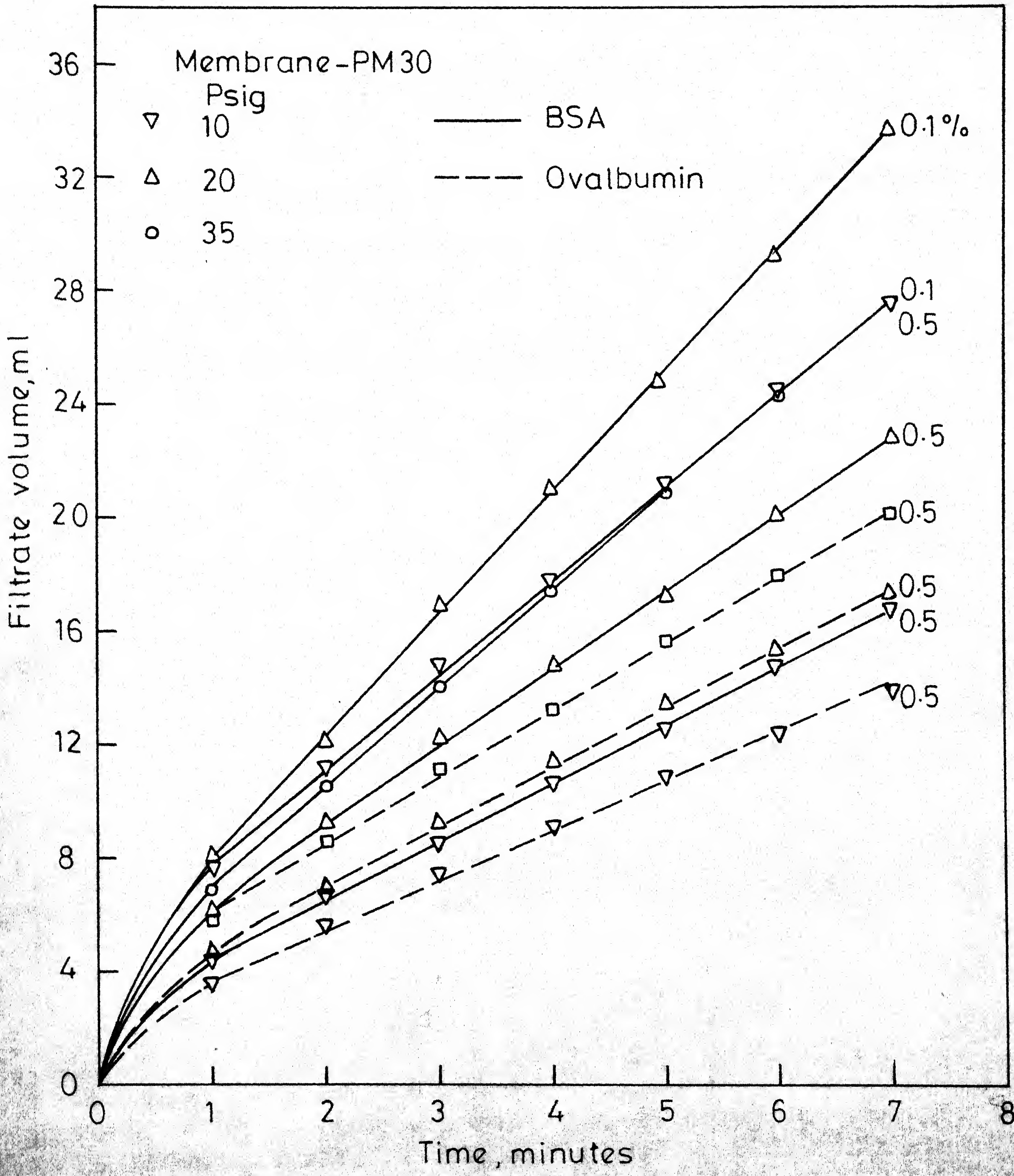


Fig. 4.6 - Ultrafiltration results for proteins at higher concentrations.

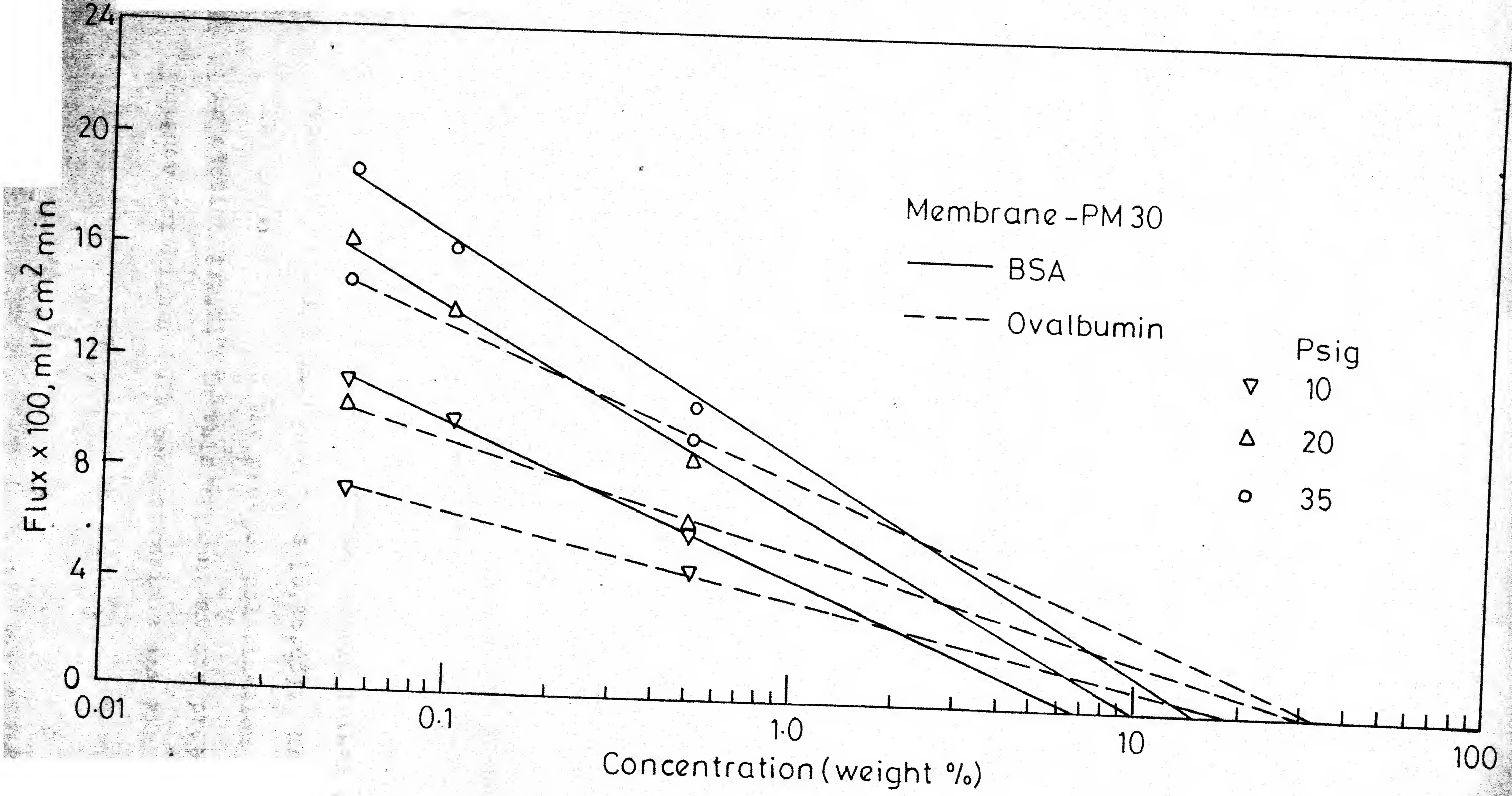


Fig. 4.7 - Effect of concentration on ultrafiltration flux.

The variation of slope with pressure indicates that the mass transfer coefficient, D_s/δ , changes with pressure. In the pre-gel polarized region, the thickness of the concentration boundary layer changes with pressure (since the Schmidt number is likely to be affected by drastic concentration changes) and since C_W changes with pressure, the solute diffusivity, which is strongly concentration dependent, can also be expected to change. Hence, the change in the slope of the plot could be justified. Similar change in slope of Flux versus log C_B curve can be observed in the results of Baker [5] also.

The concentration dependence of variation of flux with pressure is shown in Figure 4.8. It can be observed that the flux-pressure behaviour for higher concentrations is similar to that at lower concentration, i.e., the flux increases with pressure at low pressures and is invariant of pressure at high pressures. But the width of the pressure dependent region is smaller at higher concentrations, i.e., at higher bulk concentrations the flux invariance is reached at pressures lower than that for lower concentrations. Similar results showing effect of concentration on flux-pressure relation have also been reported by other investigators [5,46,63]. This behaviour is also consistent with the pre-gel polarization hypothesis discussed in section 4.2.2. In this region, at any pressure, C_W will be higher for higher bulk concentrations and will approach C_g

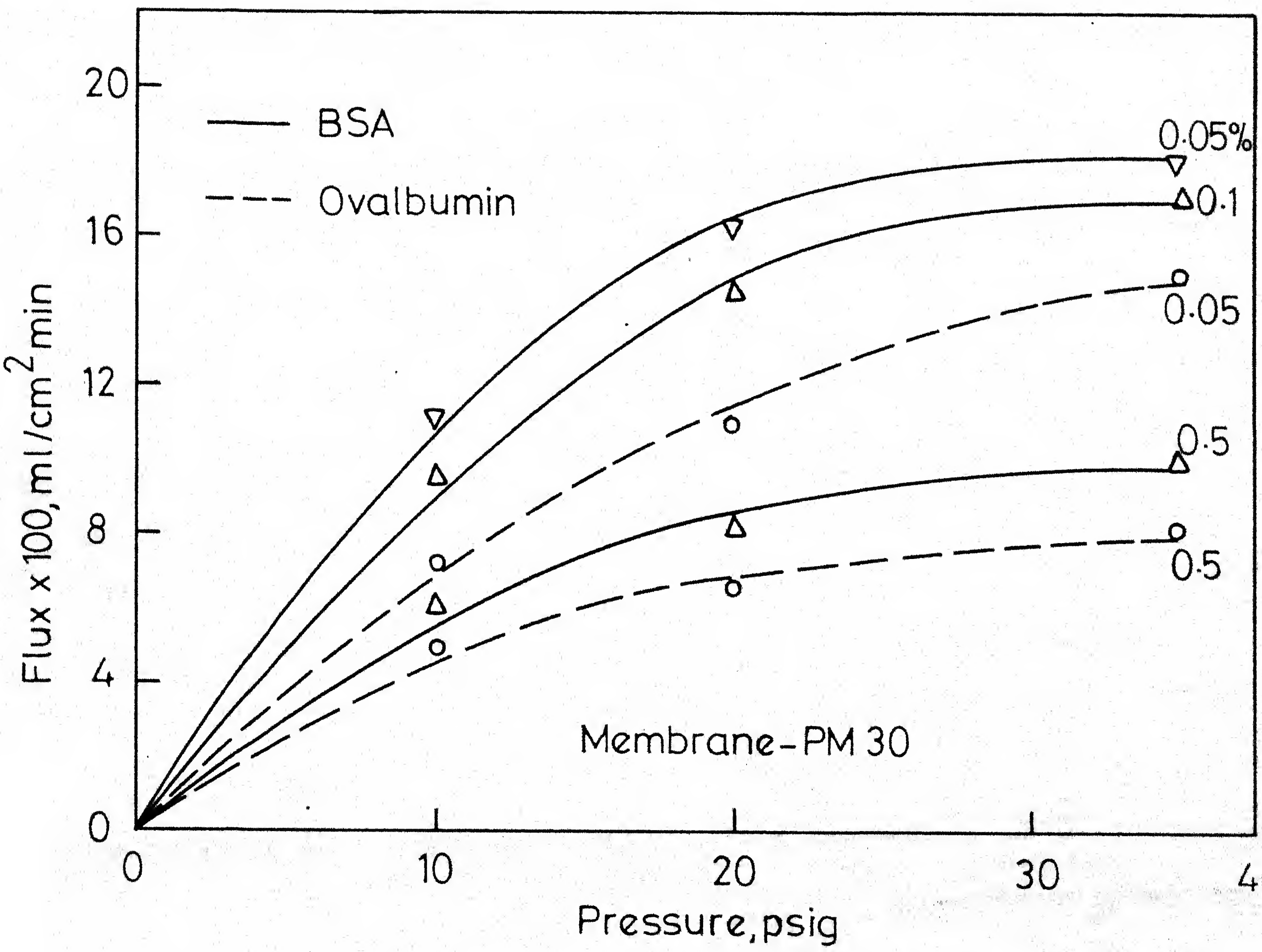


Fig. 4·8 - Effect of concentration on flux-pressure relationship.

(at which flux becomes independent of pressure) at lower pressures.

The effect of bulk concentration on the retentions at various pressures is shown in Figures 4.9, 4.10 and 4.11. The follwing observations can be made from these figures: In all cases, the retention increases with time and reaches a limiting value. The retention decreases with increasing pressure. Further, at all pressures, the retention increases with increasing bulk concentration.

The increase in retention with time has already been explained, in terms of the effect of the polarized layer, in section 4.2.2. Although the effect of pressure on solute retention at higher concentrations is similar to that at lower concentrations, the effect is less pronounced at higher concentrations, i.e., the decrease in retention with increasing pressure is less at higher bulk concentrations. Also, at higher pressures the retentions are nearly the same.

While the effect of bulk concentration on UF flux has been widely reported, very little information is available on the effect of concentration on solute retention. According to Hopfenberg et al. [46], the retention should be independent of bulk concentration in the gel polarized region and indeterminate in the pre-gel polarized region. But in their experiments with UM 05 membranes in the gel polarized region, they found the retention to increase with bulk concentration for

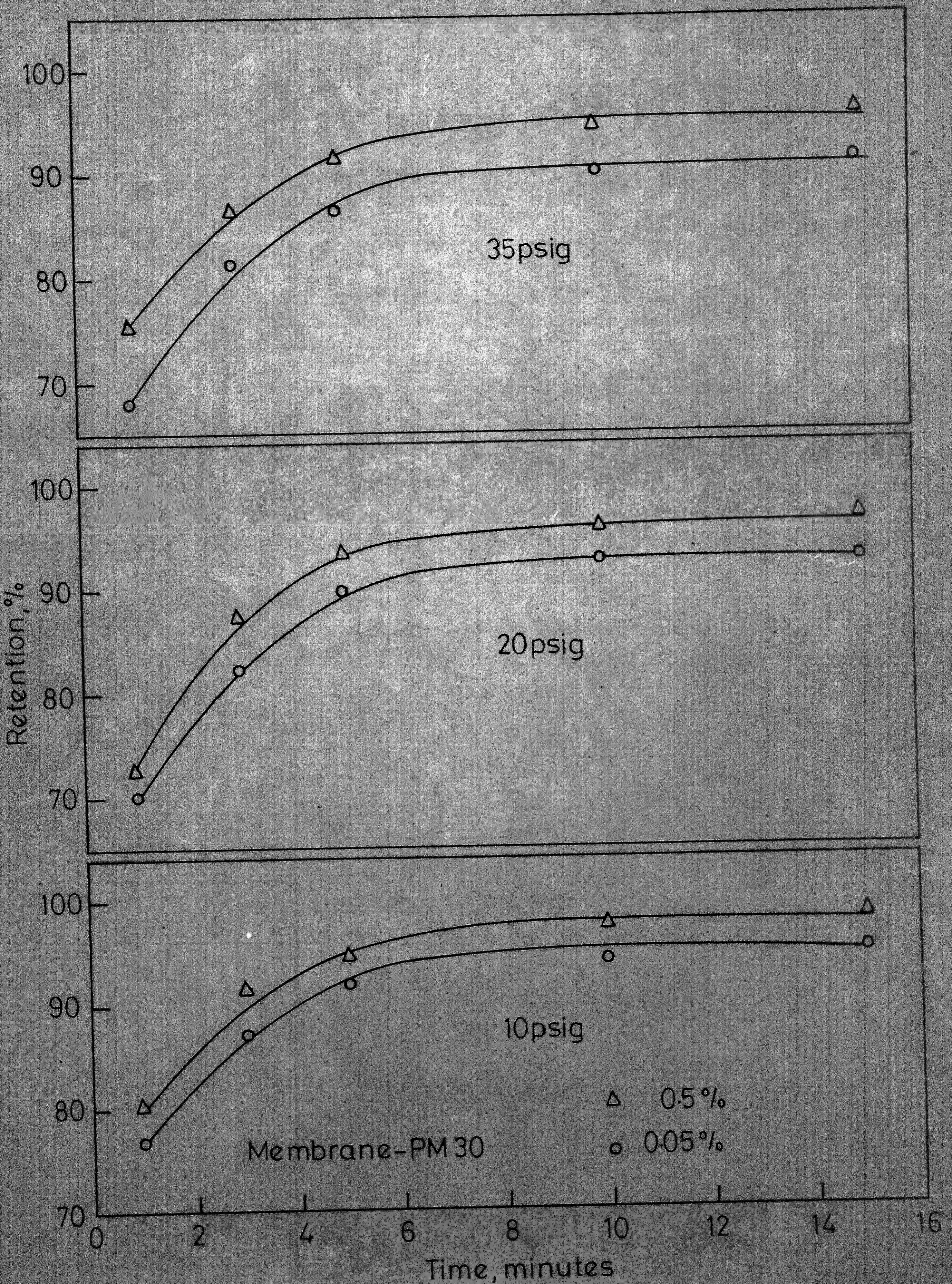


Fig. 4.9 - Effect of concentration on retention of Ovalbumin at different pressures.

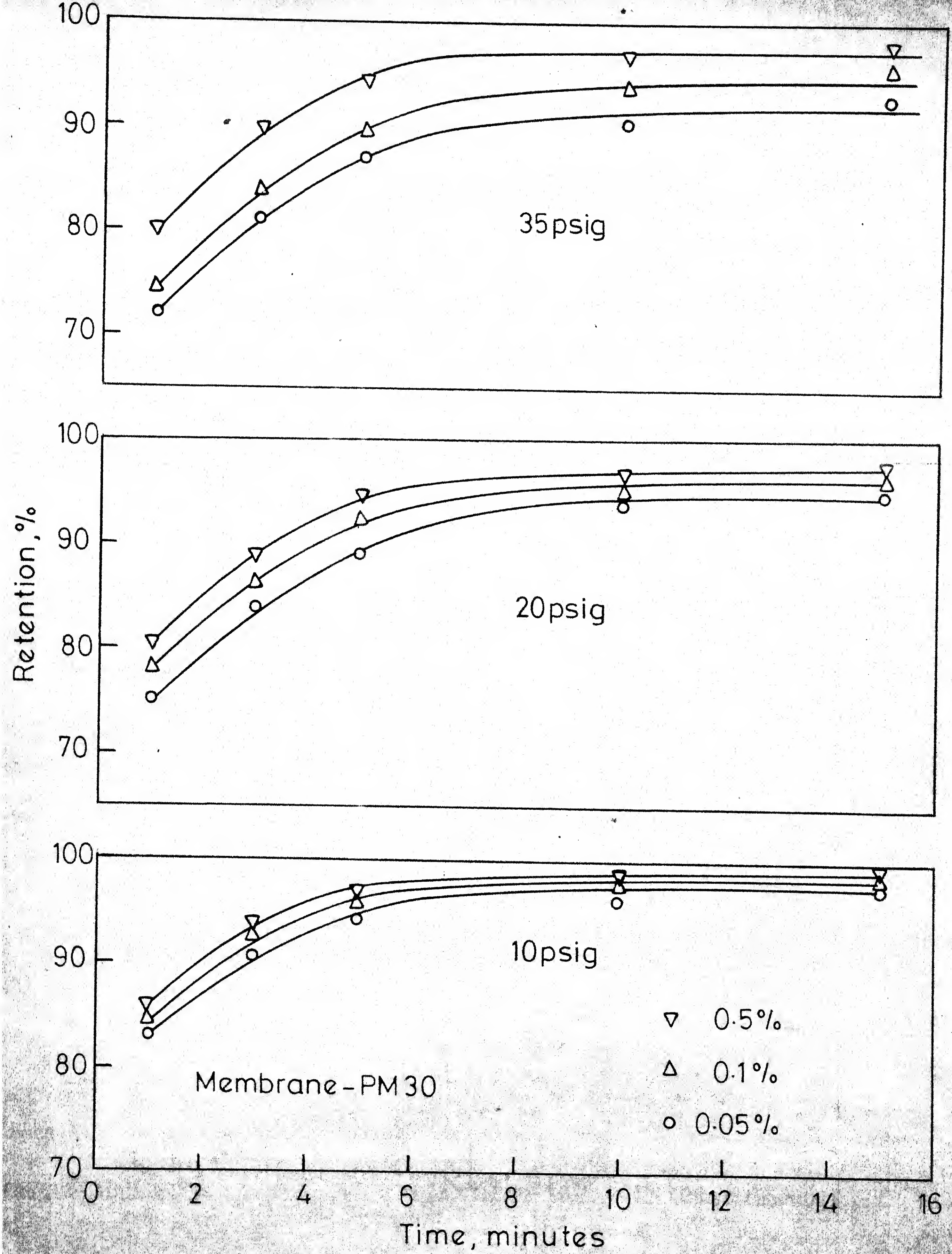


Fig. 4.10- Effect of concentration on retention of BSA at various pressures.

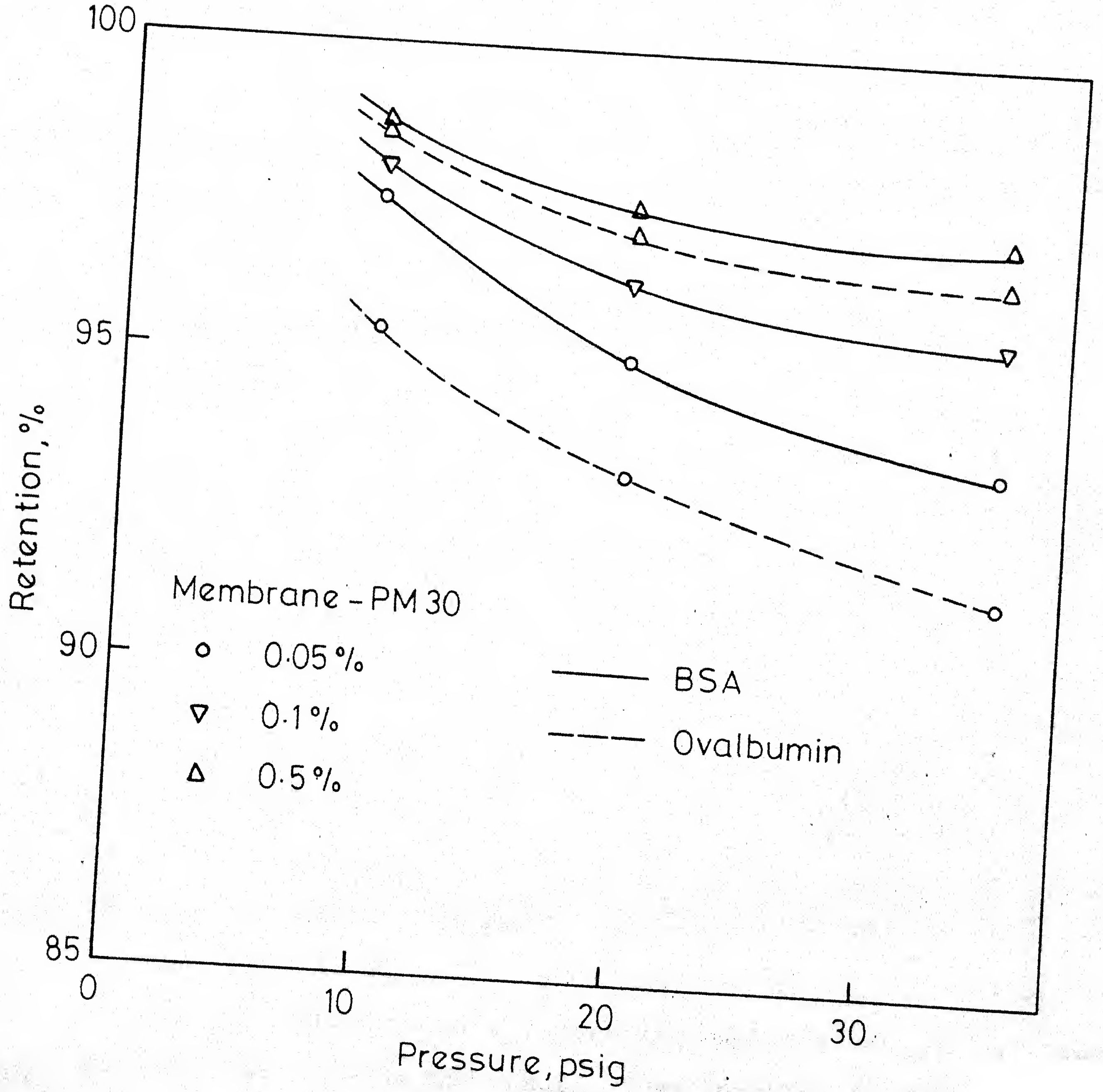


Fig. 4.11 - Effect of concentration on retention at various pressures.

some detergents and decrease with concentration for Carbowax. They attributed this to solute assymetry and interaction with the membrane. GoldSmith [40] proposed a sieving model according to which, the retention in the gel polarized region increases with bulk concentration. But, in the study of UF of dextrans and Carbowax at low pressures [39,40], he found the permeate solute concentrations increasing with increasing feed concentrations leading to either constant or decreased rejection. This was attributed by him to the relatively higher increase in solute fluxes compared to the smaller increase in C_W. Dorson et al. [29], have observed, in their study of tracer passage through protein deposits, a variation of rejection with bulk fluid tracer concentration. This was ascribed to the blocking effect of proteins and binding of tracer molecules to proteins (solute-solute interaction). A theoretical model based on these was derived by Cotter [22]. Blatt et al. [15] have pointed out that microporous UF membranes frequently show an increase in retention with increasing bulk concentration. They explained this to be the result of an increase in the solute drag on the pore walls with increasing solute concentration which, reduces the flow through pores passing the solute. This biases the flow infavour of pores too small to accomodate the solute thereby increasing the retention.

The results of the present study may be explained in the following manner: According to the pre-gel polarization hypothesis, higher bulk concentrations, which provide higher C_W, should result in reduced retention at the same pressure. On the other hand, higher wall concentration should give rise to denser layer which will increase retention, as was argued for retention increase with time. Another factor which will also increase retention is the compression of the layer by the applied pressure. Apparently the latter factors overweigh the former and the retention increases with concentration.

The compressible nature of the polarized layer has been suggested by Dejmek [27] and Dorson et al. [29] also. In the study of solute passage through deposited protein layers Dorson et al. [29] found that even the minimal deposit formed with a pressure drop of 3.35 psig offered a significant resistance to the passage of tracer molecules and the rejection increased with increasing applied pressure. Dejmek [24] also argues that the polarized layer is compressible and the resistance of the layer is proportional to the amount of deposit and increases with increasing pressure.

The results of the present investigation also support the argument of compressibility of the concentrated layer. An increase in pressure or concentration results in higher amounts of deposits and therefore, should increase retention. Thus the

relatively lesser decrease in retention at higher pressures and the increase in retention at higher bulk concentrations can be considered, to some extent, to be due to compression of the polarized layer. This is further confirmed by the relative magnitudes of the calculated resistances of the concentrated protein layer on the membrane surface, which will be discussed later.

The estimates of the time to reach steady state at higher concentrations are also shown in Table 4.1. It can be seen that as the bulk concentration increases, the time to reach steady state, at any pressure, decreases. This observation is consistent with the concentration polarization model. Since at higher bulk concentrations solute flux towards the wall is higher, C_W approaches C_g faster and this results in a quicker attainment of the steady state for a given mass transfer coefficient for back diffusion.

It should however be noticed from Figures 4.5, 4.9 and 4.10 that the time required to attain steady state with regard to solute retention, $\tau_{ss\ retention}$, appears to be higher than the time required to attain steady state in solvent flux, given in Table 4.1. Since the change in solute retention with time is also due to the formation of the gel layer, the exact reason for this behaviour is not known. The explation may be as follows:

If the compression of a forming gel layer does not affect the solvent flux strongly, a reasonable assumption in view of the sizes of the solute and the solvent, then τ_{ss} will be reached earlier than $\tau_{ss\ retention}$, since even slight compression is likely to affect the solute retention due to changes in porosity of the gel layer.

4.2.4 Effect of Membrane Permeability:

In any membrane application., the choice of the membrane is governed by two factors, namely, the solvent flux and the solute retentivity. The early isotropic microporous membranes had a wide range of pore size distribution. Consequently, membranes with higher solvent flux exhibited lower solute retentivity and were also more susceptible to plugging. The development of anisotropic membranes has made it possible to achieve higher solvent flux without much loss in solute retentivity and with much less plugging.

The general practice in UF is to choose a membrane which has a cut-off level much below the molecular weight of the solute to be separated so that essentially complete retention may be achieved. Consequently, not much work has been reported in the literature on the performance of UF membranes with partial permeability to a solute. But, as we have seen earlier, in the UF of macromolecules, the membrane controls the process only for a short time at the beginning. Further, as described in Chapter 2,

concentration polarization leads to the formation of a cake of solute molecules on the membrane surface which acts as a dynamic, secondary membrane whose flux and retention behaviour is very much different from that of the primary membrane. We have already seen how this layer controls the UF performance and the effect of pressure and bulk solute concentration on the UF performance. If the polarized layer controls the UF performance, the choice of the membrane becomes important only in so far as it affects the phenomenon of concentration polarization.

To investigate the effect of membrane permeability on UF performance, experiments were conducted with more open membranes XM100A and XM300, having partial permeabilities to the solutes used in this study. The results are shown in Figures 4.12,4.13,4.14 and 4.15. These plots show the same trend as was observed earlier for the tighter membrane, PM30, i.e., the rate of filtration decreases with time and reaches a steady state, due to concentration polarization.

The steady state UF fluxes are plotted against the applied pressure for these membranes in Figure 4.16. For the sake of comparison, the flux-pressure behaviour for the tighter membrane, PM30, is also plotted in the same figure. The following observations can be easily discerned from this figure. The flux-pressure behaviour shows the same trend for all the membranes.

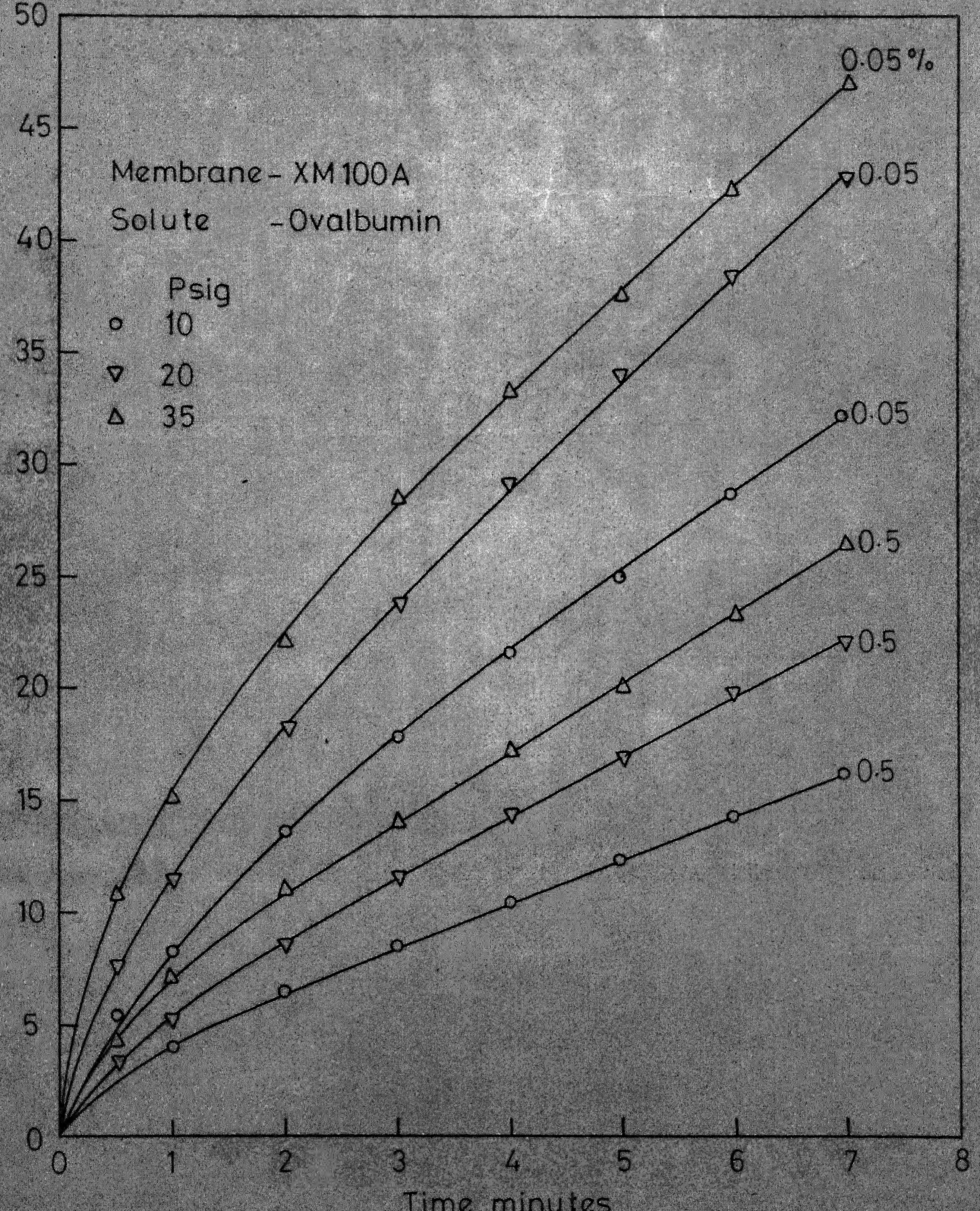


Fig. 4·12 - Ultrafiltration results for Ovalbumin - XM 100A membrane.

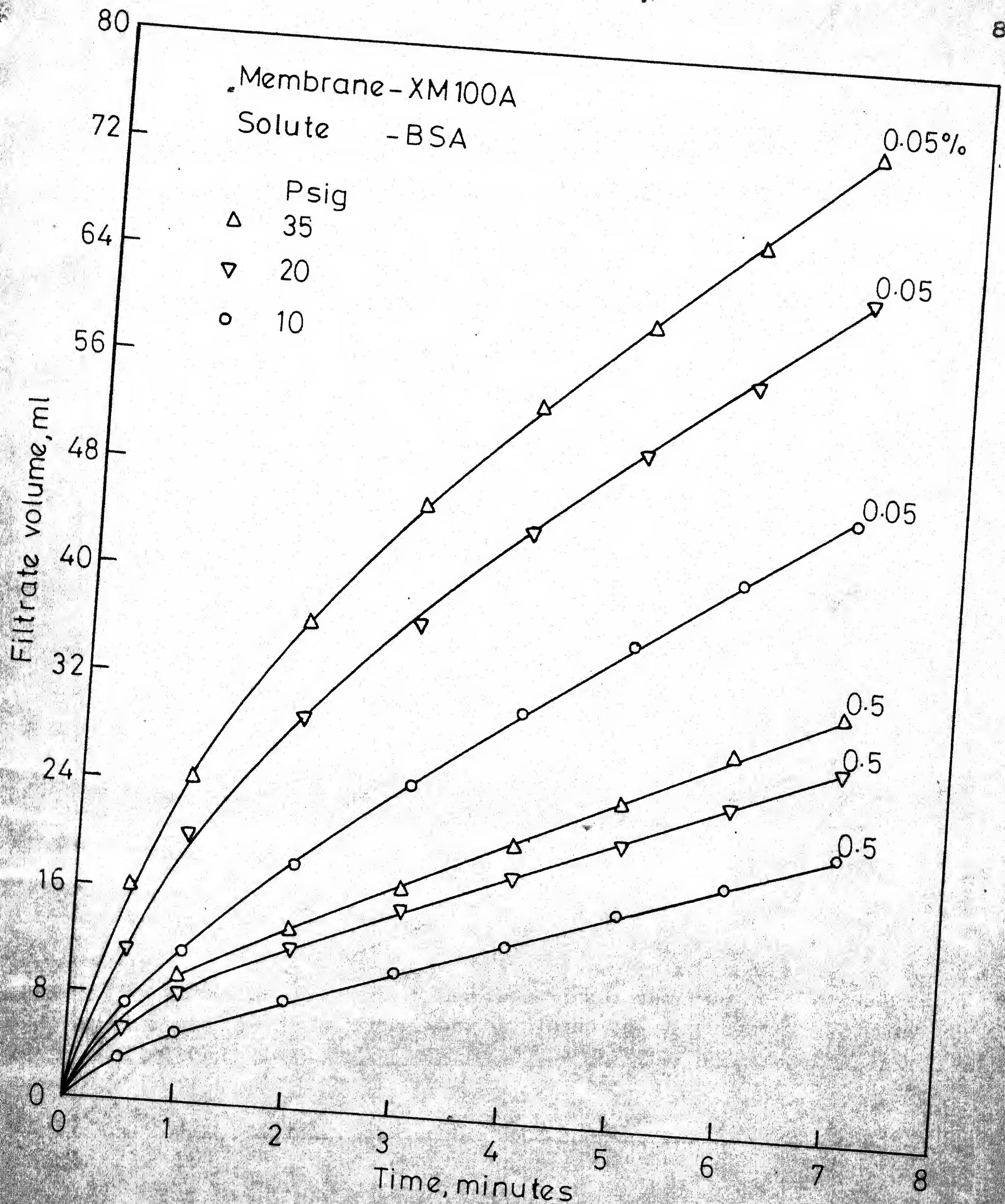


Fig. 4.13 – Ultrafiltration results for BSA-XM100A membrane.

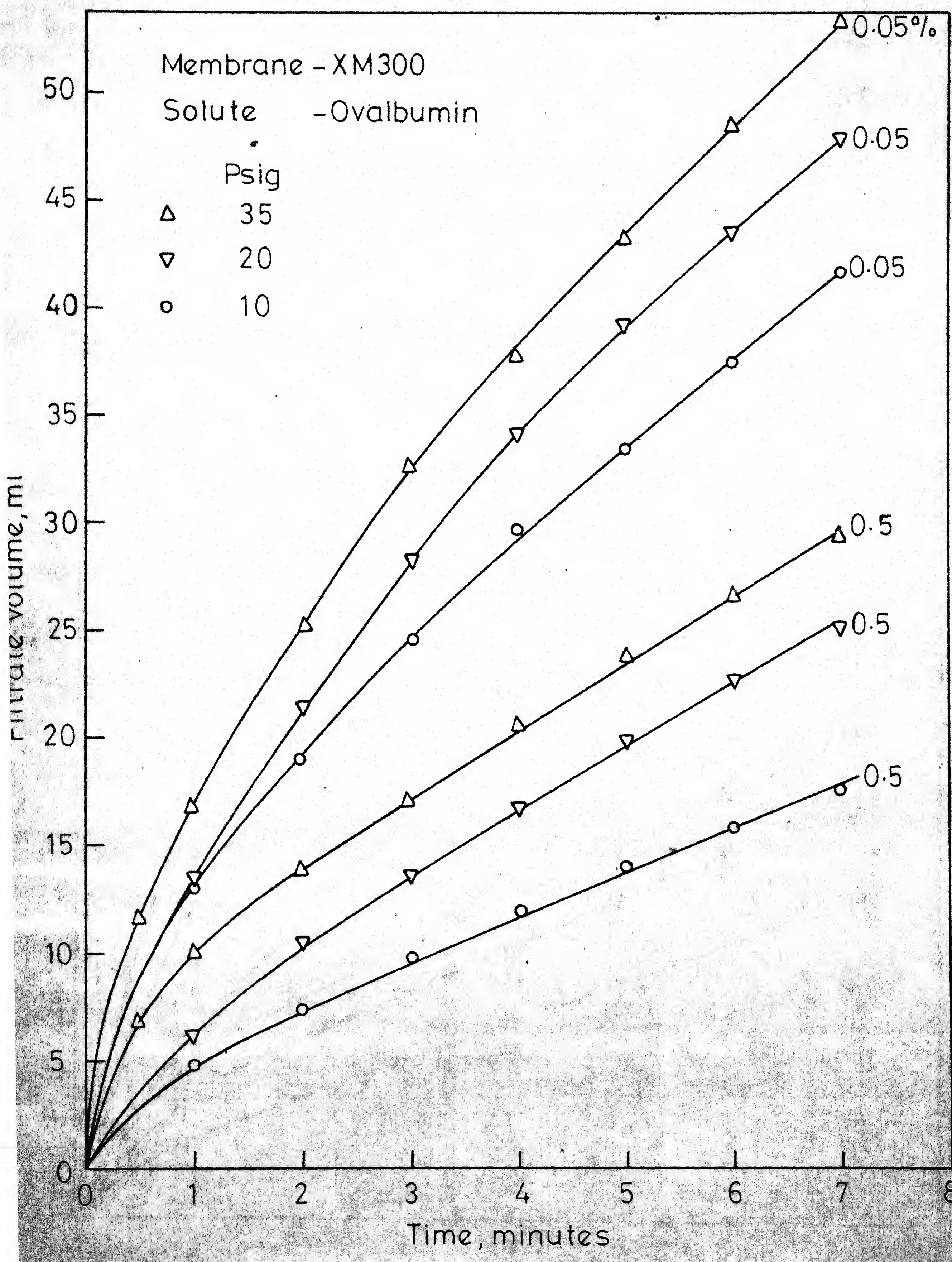


Fig. 4·14 – Ultrafiltration results for Ovalbumin-XM300 membrane.

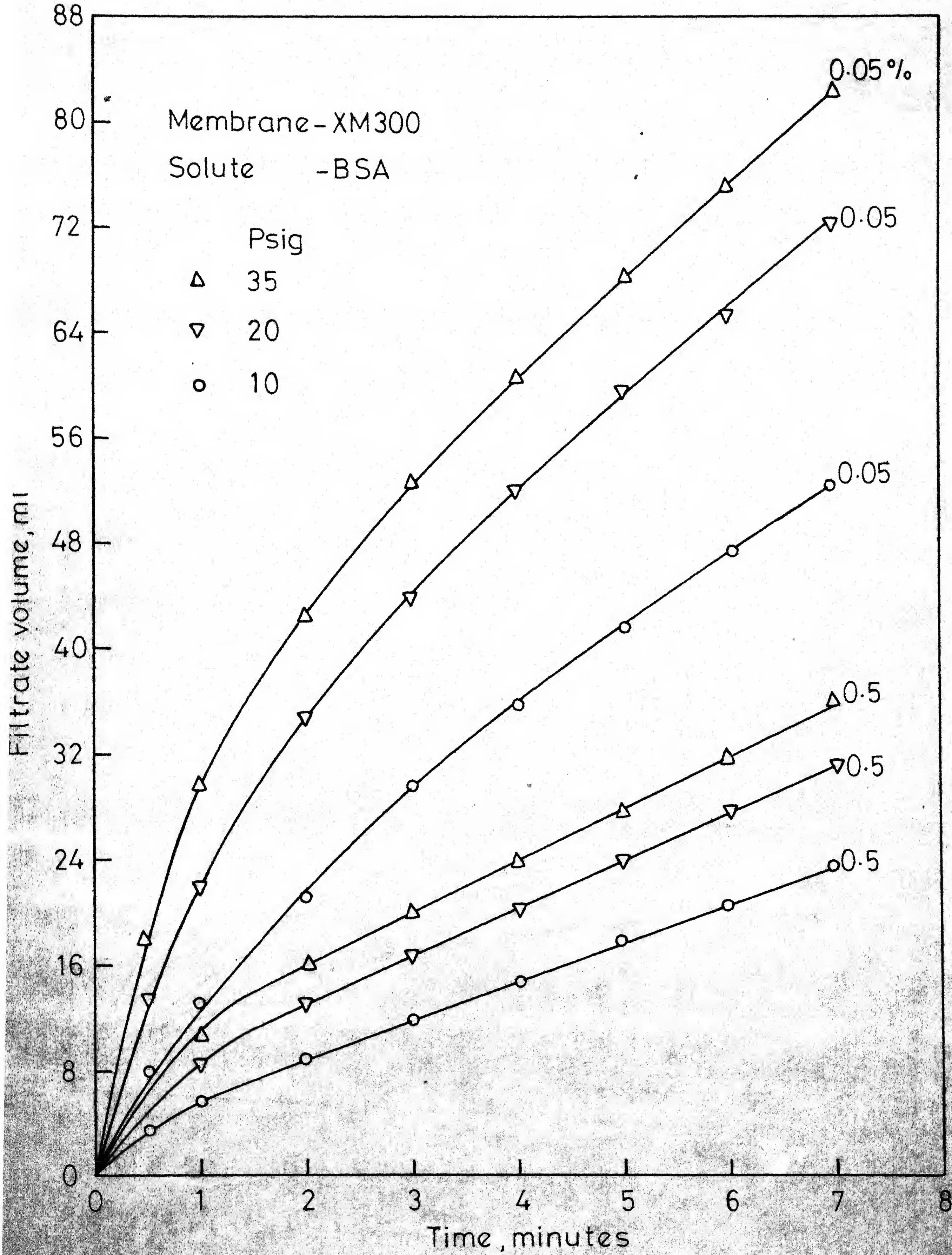


Fig. 4.15 - Ultrafiltration results for BSA-XM300 membrane.

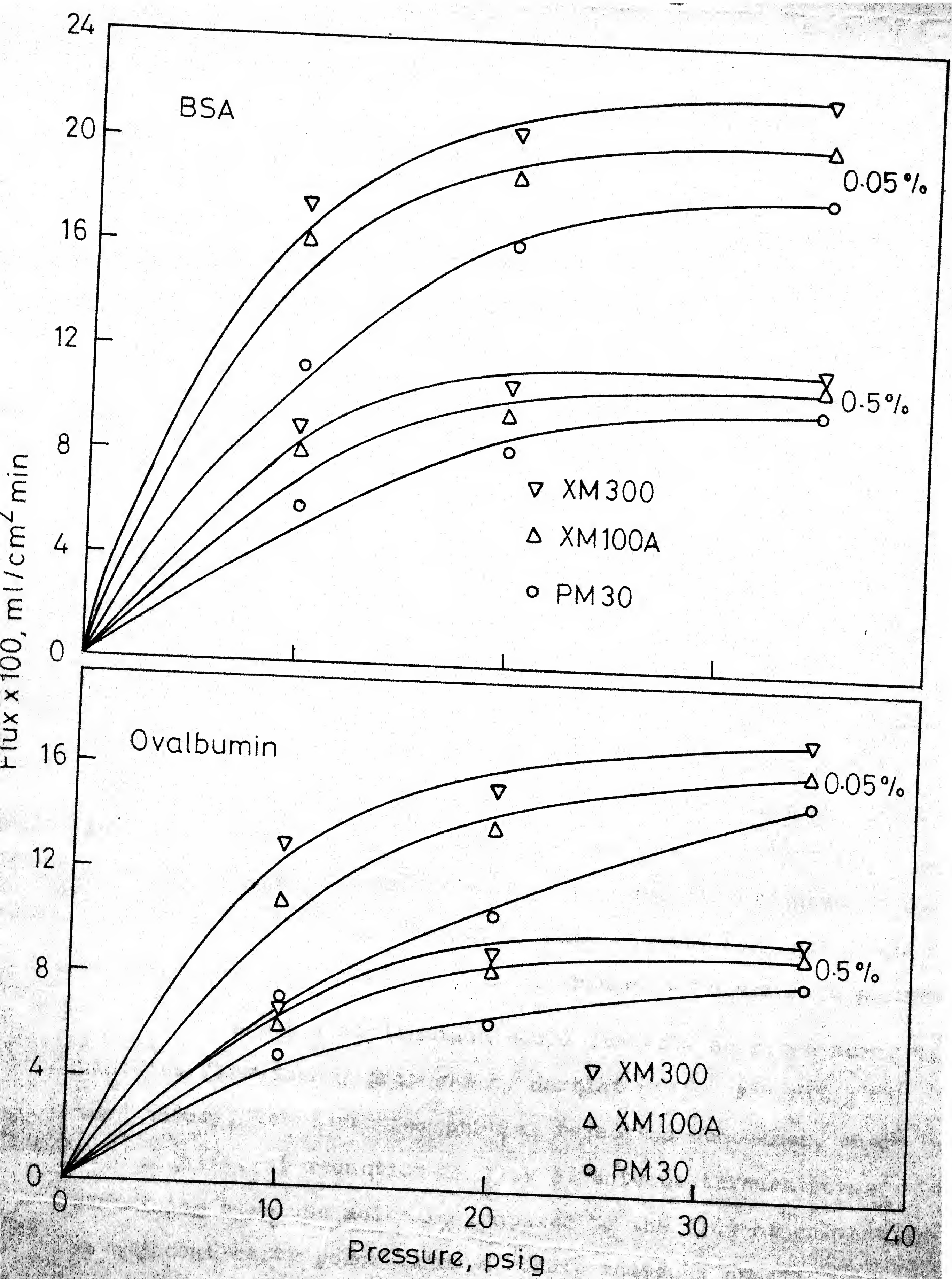


Fig. 4.16 – Effect of membrane permeability on flux–pressure relationship.

This indicates that the polarized layer controls the UF performance with all the membranes. Also, in general, at low pressures the flux increases with membrane permeability, but at higher pressures, particularly at higher bulk concentrations, the UF flux is nearly invariant of the membrane permeability. This behaviour could be explained, qualitatively, along the lines similar to that used for explaining the effect of pressure on flux. At low pressures, where pre-gel polarization hypothesis is valid, the increased forward transport through the more open membrane results in more solute being brought to the membrane surface. Consequently, C_W increases, thereby increasing the back transport, resulting in a net increase in UF flux. But, at higher pressures, which is near the gel polarized region, C_W approaches C_g and the back transport reaches a limiting value. In this region, the use of more open membrane merely results in a thicker layer of retained solutes and the flux reduces to the value limited by back transport. Blatt et al. [15] and Baker [5] have also observed similar flux invariance with membrane permeability.

Another explanation could probably be given using the hindered flow theory proposed by Harriot [45]. According to this theory, developed for partial rejection membranes, there is a significant reduction in flow of solvent through pores containing a solute molecule compared to the flow of solvent in an adjacent empty pore. Also, a solute molecule spends

proportionately more time in smaller pores than in larger pores which tends to decrease the effective average pore size and there is a significant reduction in flow even with uniform cylind..ical pores. Thus, at low pressures, probably not all the larger pores of the open membranes are occupied by the solute molecules and the flux increases. As the pressure and concentration are increased, C_W increases and more and more of the larger pores are covered by solute molecules leading to the invariance in flux.

Another aspect to be observed in Figure 4.16 is that the width of the pressure dependent region is a function of membrane permeability. The threshold pressure at which the flux becomes independent of pressure is lower for membranes with higher water permeability compared to that for a lower water permeability membrane. This observation can also be explained by the pre-gel polarization hypothesis. At any pressure, the higher initial transport rates through more open membranes cause a higher concentration polarization modulus (higher ratio of C_W to C_B) so that C_W approahes C_g at lower pressures. Similar flux-pressure dependence on membrane permeability has also been reported by Blatt et al. [15] and Fane [33].

Retention characteristics were also studied as a function of membrane permeability and the results for the higher water flux membranes XM100A and XM300 are plotted in Figures 4.17, 4.18, 4.19 and 4.20.

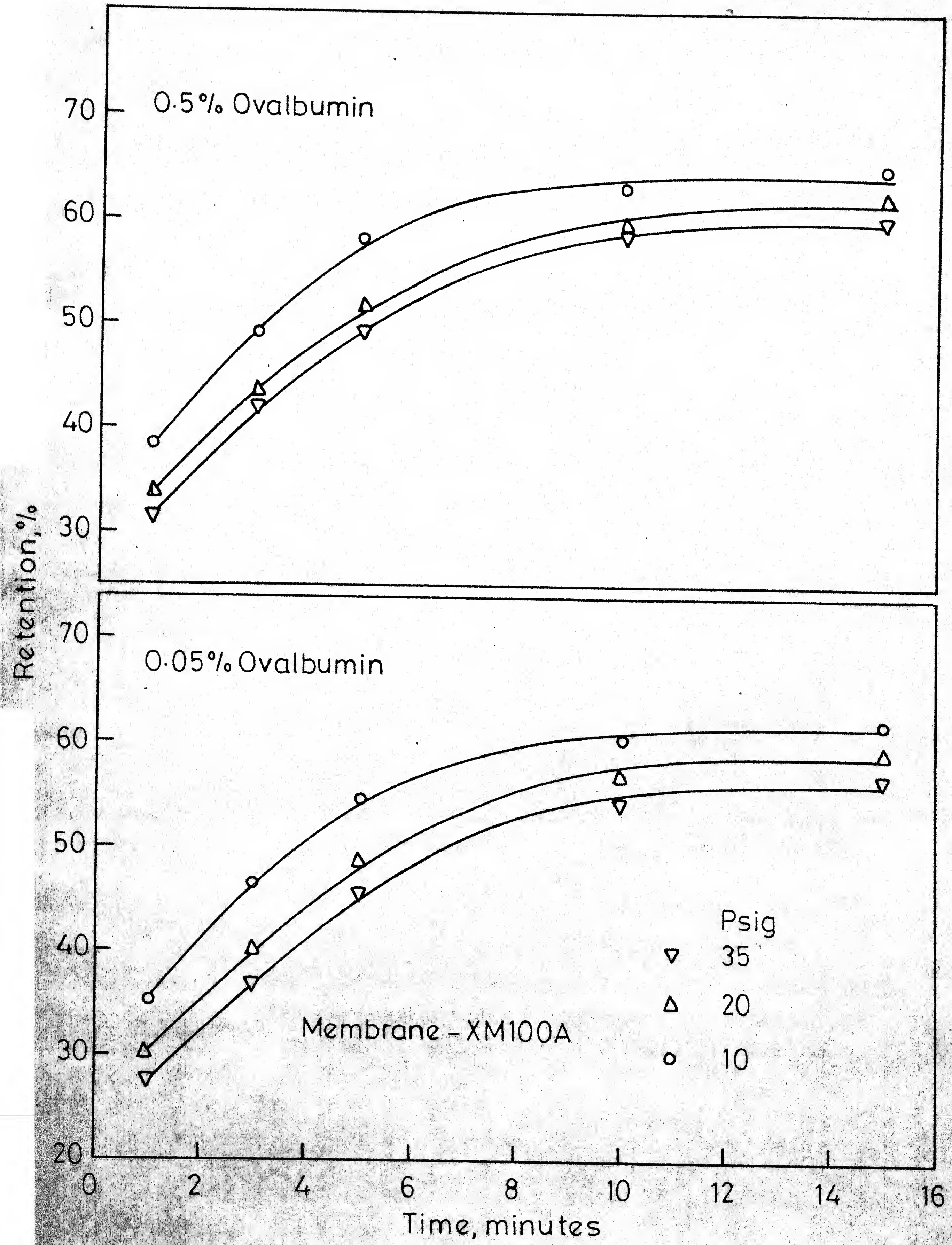


Fig. 4.17 - Retention results for Ovalbumin through XM100A membrane.

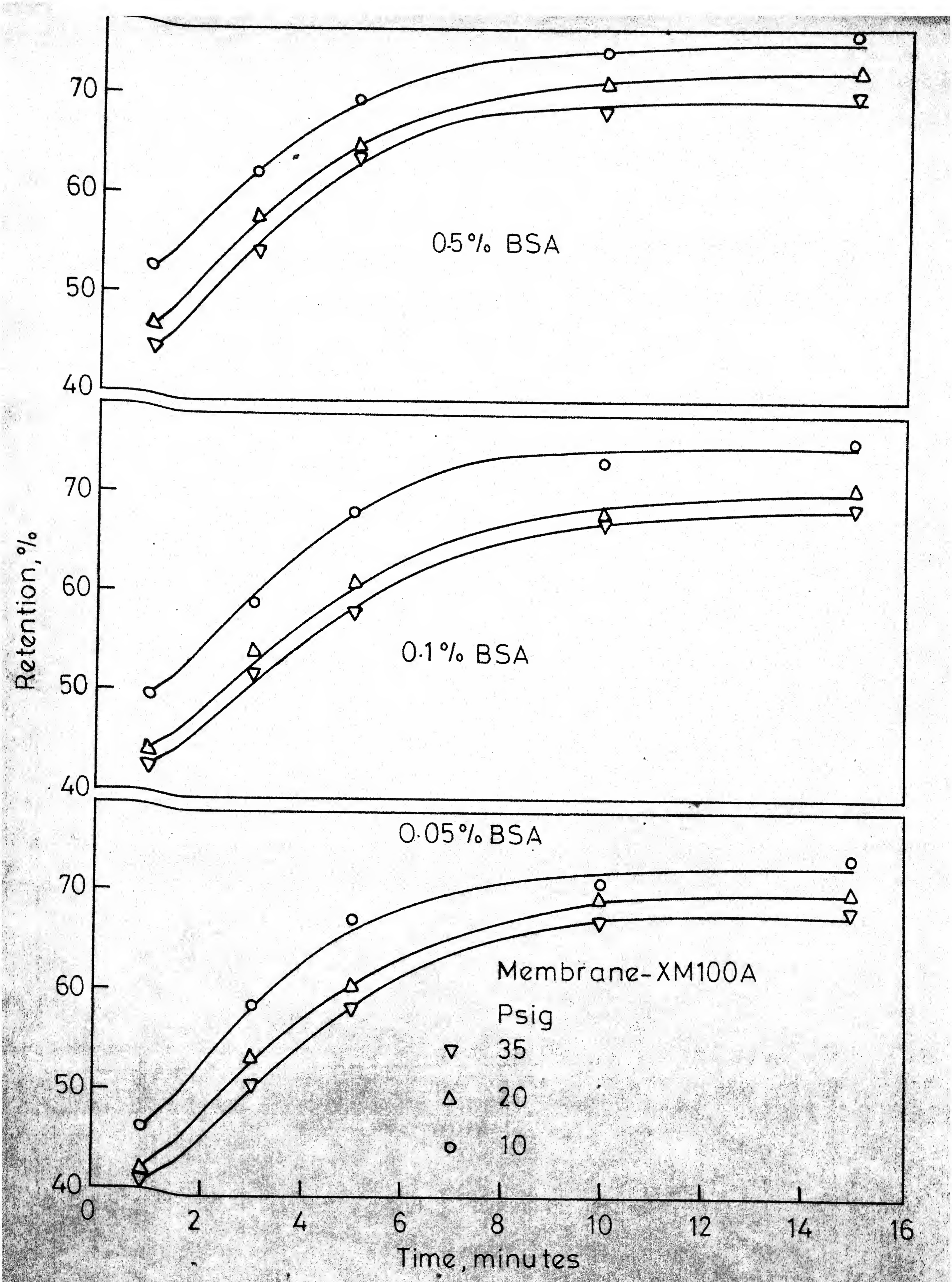


Fig. 4.18 - Retention results for BSA through XM 100 A membrane.

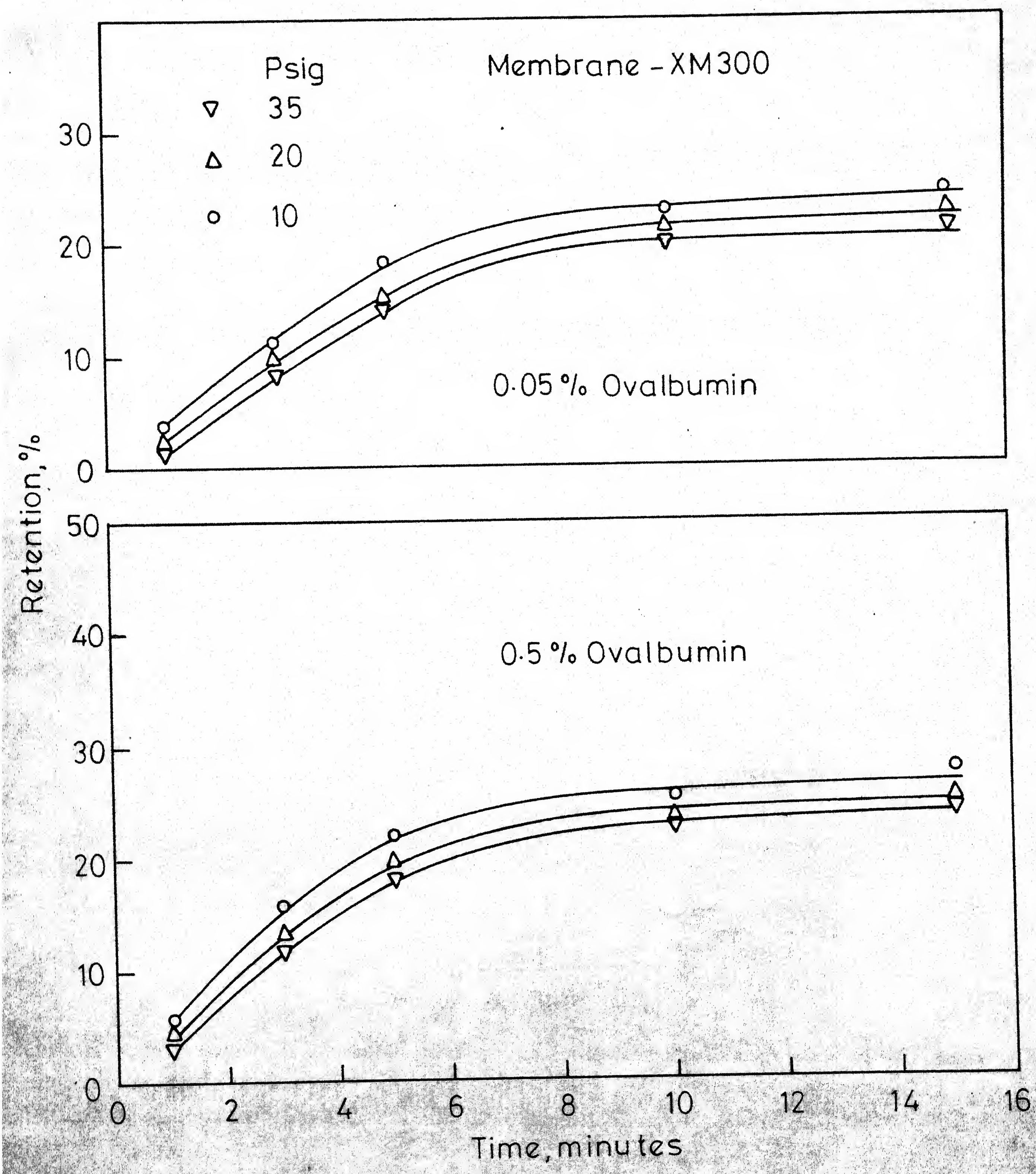


Fig. 4.19 - Retention results for Ovalbumin through XM300 membrane.

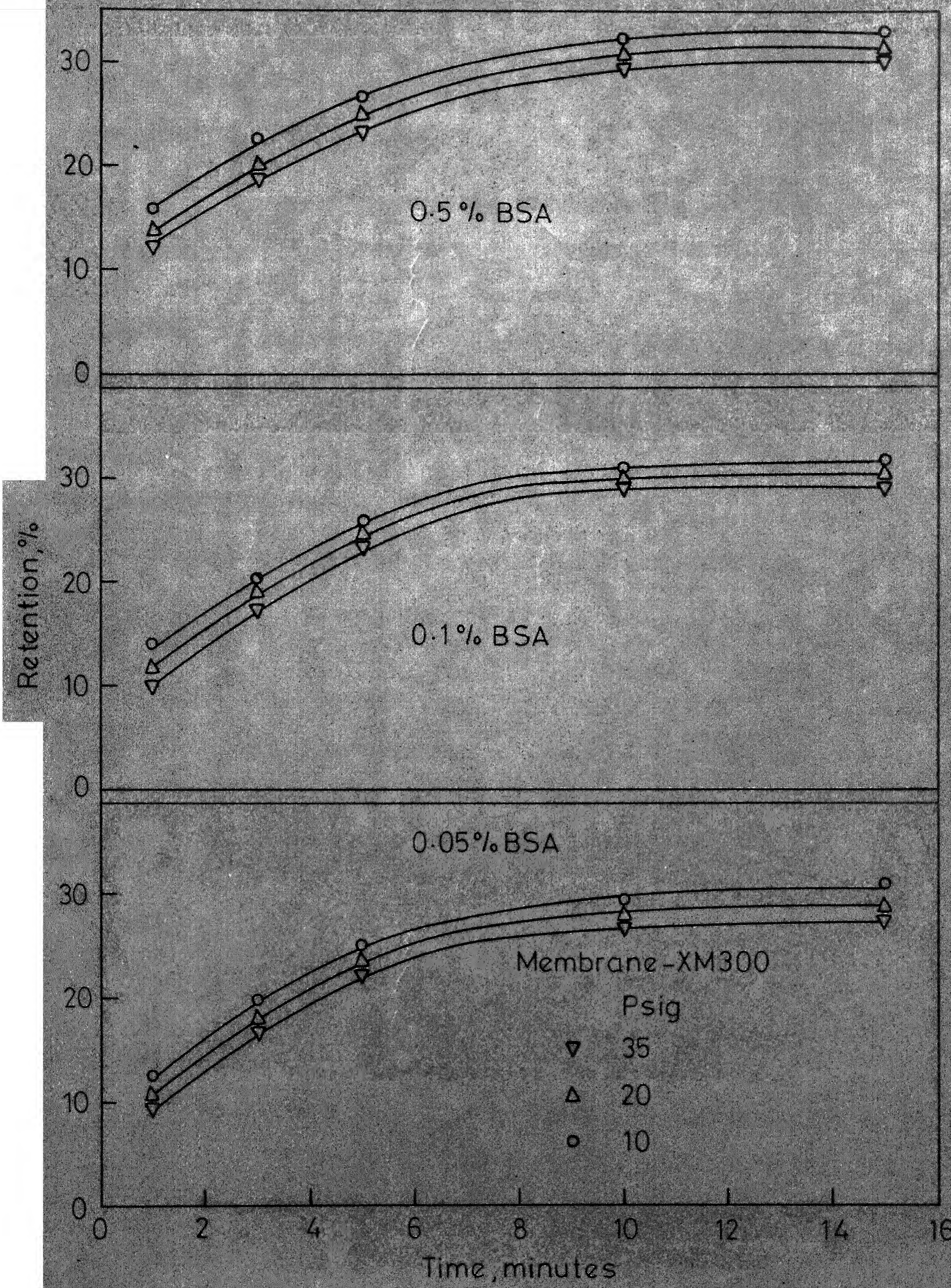


Fig. 4.20 - Retention results for BSA through XM300 membrane

Before discussing these results, it is necessary to point out that no work has been reported in the literature on the retention behaviour as a function of membrane peremeability for single solutes under similar conditions. This is probably because of the criteria for the choice of the membrane. As was explained earlier, the general practice is to choose a membrane which ensures complete retention of the solute. The only source available for obtaining some information on the retention behaviour of different membranes is the manufacturer's catalog.

Membranes with differing water permeabilities have been used, in general, only for fractionation of a mixture of solutes. Thus, Blatt et al. [13] have studied the fractionation of mixtures of proteins and polyethylene glycols by graded retention membranes. They found that the membrane retentivities were altered due to concentration polarization. Baker [4] fractionated a mixture of linear polymers through polyelectrolyte membranes and obtained good separation. Michaels et al [60] have reported the fractionation of defatted milk whey, which is a complex mixture of proteins of diverse molecular weights, through a cascade of membranes with differing molecular weight cut-offs. They found that the lowest molecular weight fractions of the mixture passed through the membranes with higher molecular weight cut-offs unimpeded by the polarized layer. But the medium molecular weight fractions were greatly hindered by the

polarized layer and were unable to pass through even the most open membrane. Harriot [45] proposed a mechanism for partial rejection of solutes by UF based on hindered flow theory. He found that the rejection depends on the product flow rate, molecular shape and diffusivity and membrane structure.

The results of the present study indicate that the retention patterns for the open membranes, XM100A and XM300, (Figures 4.17to 4.20) are similar to that of the tighter membrane, PM 30 (Figures 4.9 and 4.10) i.e., the retention increases with time and reaches a steady value. It is evident from the results that concentration polarization takes place with the open membranes also and alters the membrane performance just as it does for the tighter membrane. The effects of pressure and bulk concentration on the retention for these membranes also show the same trend as that for the tighter membrane as can be observed from Figure 4.21. The retention decreases with increasing pressure, the decrease being less at higher pressures, and increases with increasing bulk concentration. These results, then, could also be explained by the same arguments advanced earlier in terms of the compressible nature of the polarized layer.

It is also of interest to note that the values of retentions obtained at steady state for the open membranes are higher than those quoted for these membranes by the

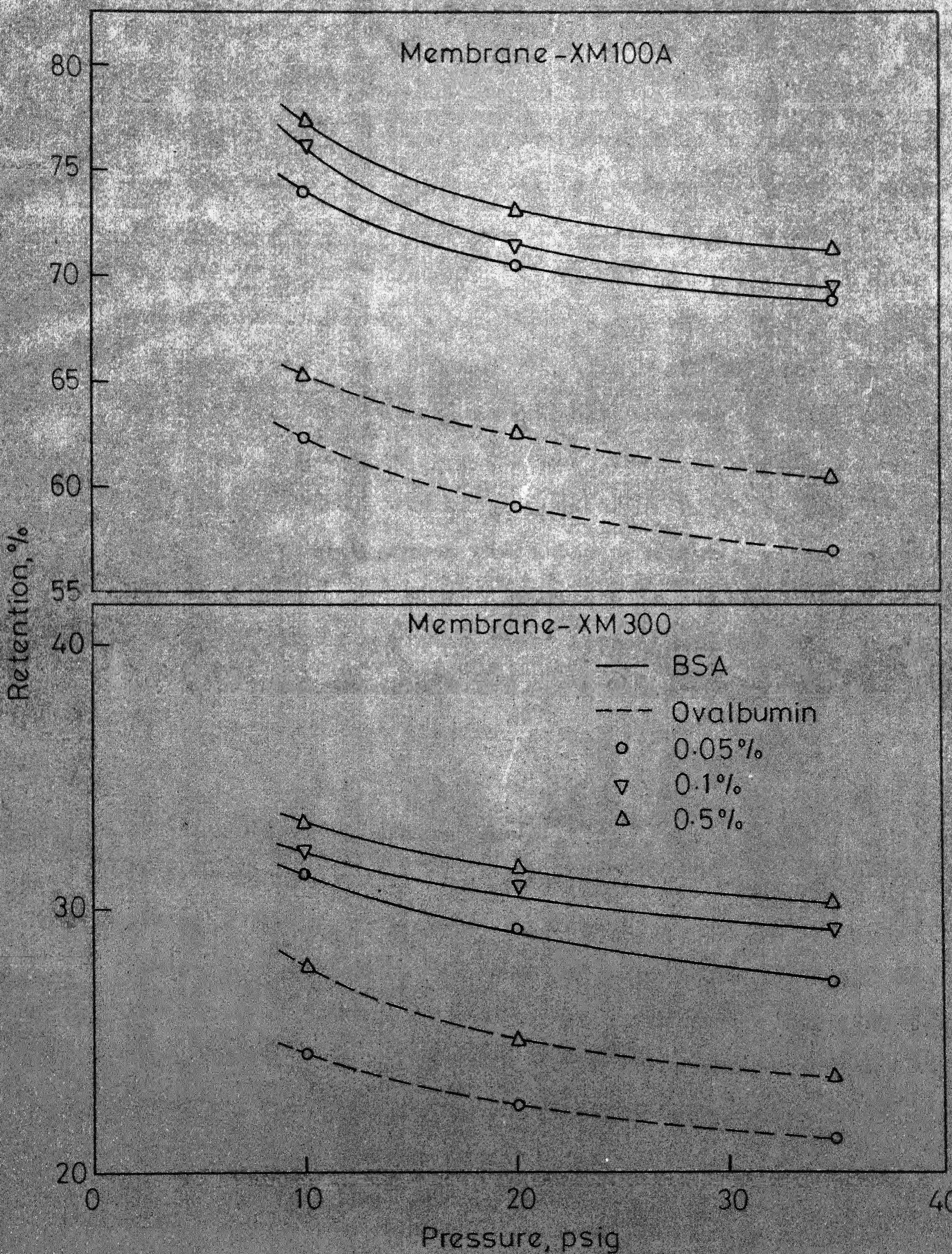


Fig. 4.21-Effect of concentration on retention at various pressures-open membranes.

manufacturers [2] (Table 3.3). Nevertheless, they are much smaller than those for the tighter membrane. On the other hand, we have seen that the steady state fluxes are nearly the same for all the membranes. If, as explained earlier, the flux invariance is merely a result of a thicker deposit on the membrane and if the gel layer controls the UF performance, one might expect the retentions of these membranes to be comparable to those of the tighter membrane. But, since open membranes contain proportionately larger number of bigger pores through which the solutes are carried, the solute concentration in the filtrate increases and the retention is reduced. Harriot [45] has also pointed out that the fraction rejected depends on product flow rate and membrane structure and the actual rejection decreases with increasing flow.

The estimates for the time taken to reach steady state for these open membranes have already been tabulated in Table 4.1. It is evident from the table that the time required to reach steady state increases with increasing permeability of the membrane. This is quite understandable since the rate of accumulation is reduced due to the increased solute flux through the membrane and the increased back transport resulting from higher C_W caused by the higher initial forward transport. But the effects of pressure and bulk concentration on the time to attain steady state with partial permeability membranes show

the same trend as that for the complete retention membrane, i.e., the time required to reach steady state increases with pressure at low pressures and decreases at higher pressures and at higher bulk concentrations the steady state is reached after a smaller time interval. The reasons for this behaviour have already been explained. The resistances of the polarized layer of these membranes have also been estimated and will be discussed later.

4.2.5 Effect of Stirring:

It was explained in Chapter 2 that the UF flux with macromolecular solutions is governed solely, due to the gel polarization phenomenon, by the mass transfer conditions in the UF system. Variables which provide better mixing of the bulk solution increase the mass transfer coefficient, enhance the back transport and reduce the effect of polarization, thereby increasing the UF rate. The methods commonly employed to promote mixing of the feed solution are, magnetically driven stirring in stirred cells [7,14,42,74], the use of static mixing elements in tubular membranes [21,26] and the thin channel UF system in which the feed solution is passed at high velocities through thin channels, lined with membrane [63]. The effects of agitation have been studied in all the cases and results have been obtained in terms of the effect on the UF flux of stirrer speed, feed velocity, Reynolds number and channel dimensions. Theoretical models have also been developed which give the mass transfer

coefficients as a function of stirrer speed or channel dimensions or channel shear rate and the experimental results have been found to be in good agreement with the theoretical models.

To investigate the efficiency of stirring in the UF system used in this study, experiments were carried out with and without stirring at 20 psig applied pressure and 0.05 percent concentration of the proteins. The results are presented in Figures 4.22, 4.23 and 4.24.

It can be seen from the data that stirring results in increased UF rate with PM30 membrane, which is in agreement with the predicted behaviour. Similar increase in UF rate with stirring have been reported by Blatt et al. [15]. In contrast, the partially permeable membranes XM100A and XM300 show an unexpected behaviour-the UF rate with stirring is lower than that without stirring. At first, it was suspected that this could be due to some leakage in the membranes. But the restoration of the original pure water filtration performance after the experiment indicated that leakage could not be the cause of this unusaul behaviour. This was further confirmed by the repeatability of this behaviour.

This unusual behaviour of the open membranes could not be justified either by the fluid mechanical considerations, as these conditions are the same for all the membranes, or by

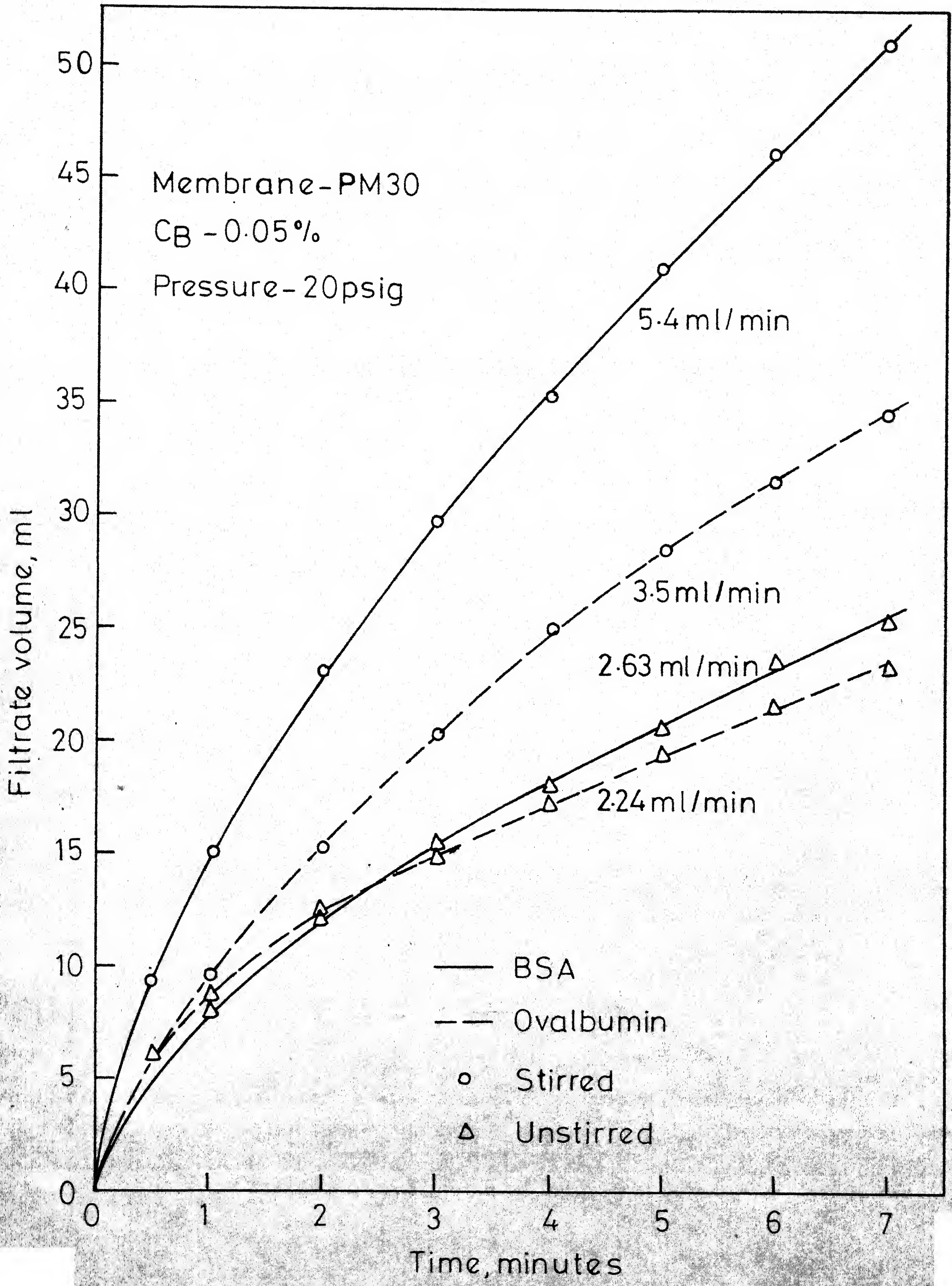


Fig. 4·22 - Effect of stirring - PM 30 membrane.

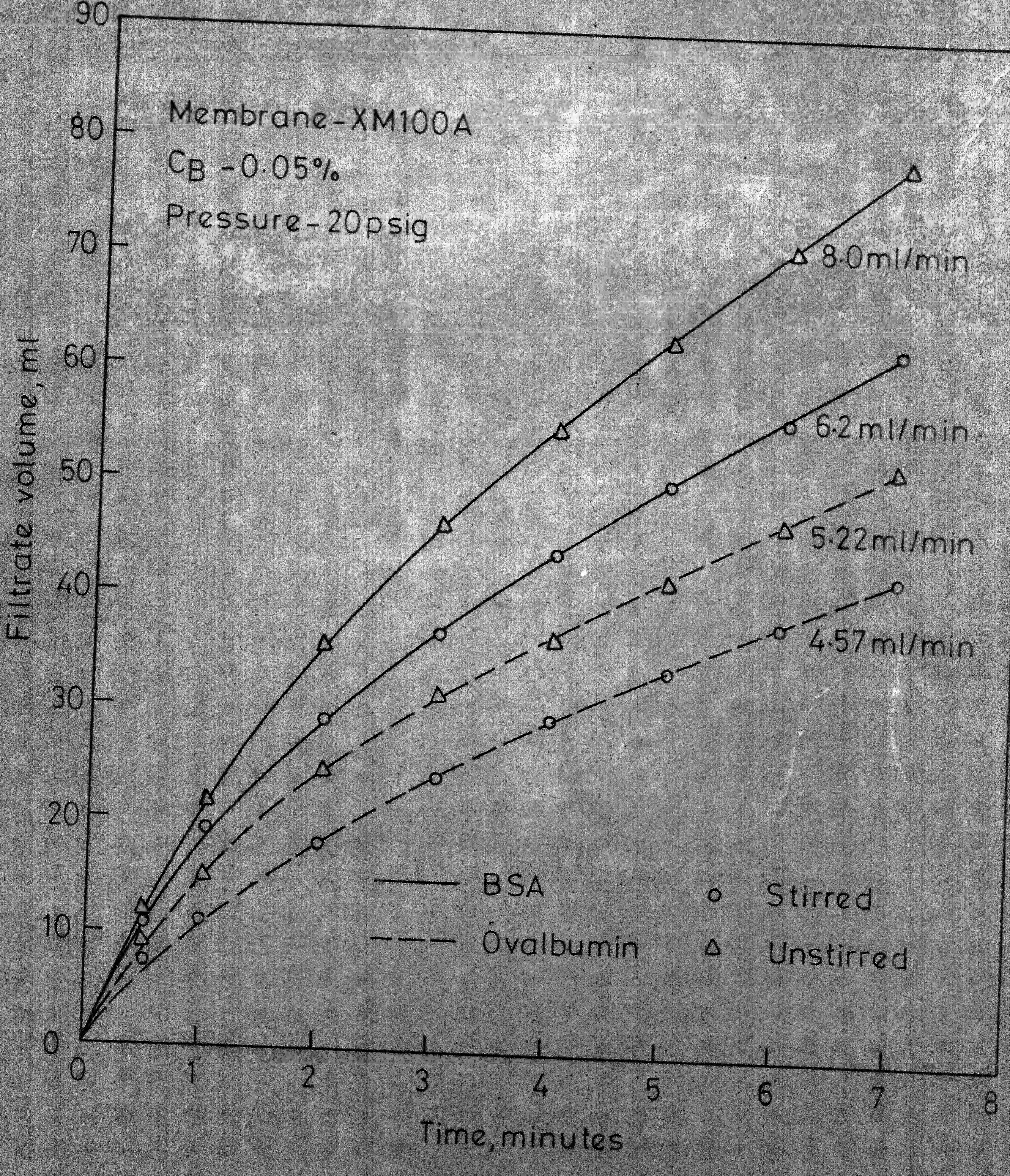


Fig.4.23 - Effect of stirring - XM 100 A membrane.

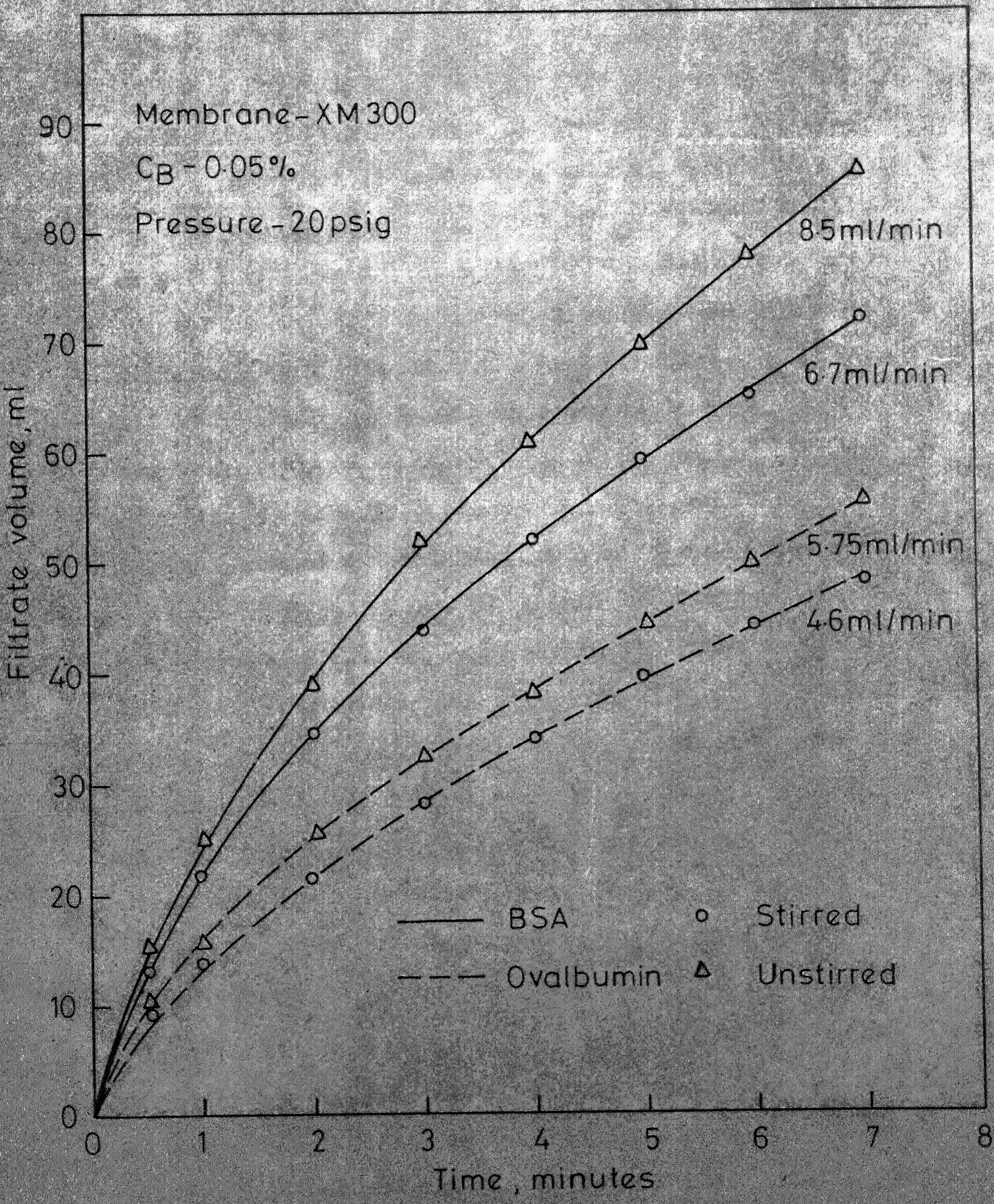


Fig. 4.24 - Effect of stirring - XM 300 membrane.

membrane interactions, since the membrane materials are also the same. This behaviour is presumably due to some change in the structure of the solute as a result of stirring and the consequent changes in the nature of the polarized layer or due to pore blocking. To test the validity of this hypothesis, two experiments were carried out. In the first, 0.05 percent BSA was filtered through XM100A membrane at 20 psig under usual stirred conditions. The retentate from this experiment was then adjusted to 0.05 percent and refiltered through the same, cleaned membrane under identical conditions. The results are presented in Figure 4.25. (It should be noted that the XM100A membrane used for these experiments was taken from a different set than that used for other initial time experiments.) It can be seen that the rate in the second experiment, with the retentate, is much lower than that in the first, with fresh solution. Since all other conditions are same in both the experiments, this is probably due to more pronounced change in the solute molecules as a result of stirring in the first experiment.

It has been known for some time that long chain molecules can be broken mechanically both in solution and in bulk phase. In dilute solutions the degradation occurs as a result of molecular stresses developed by hydrodynamic shear. Many studies dealing with such degradation of both synthetic and biological

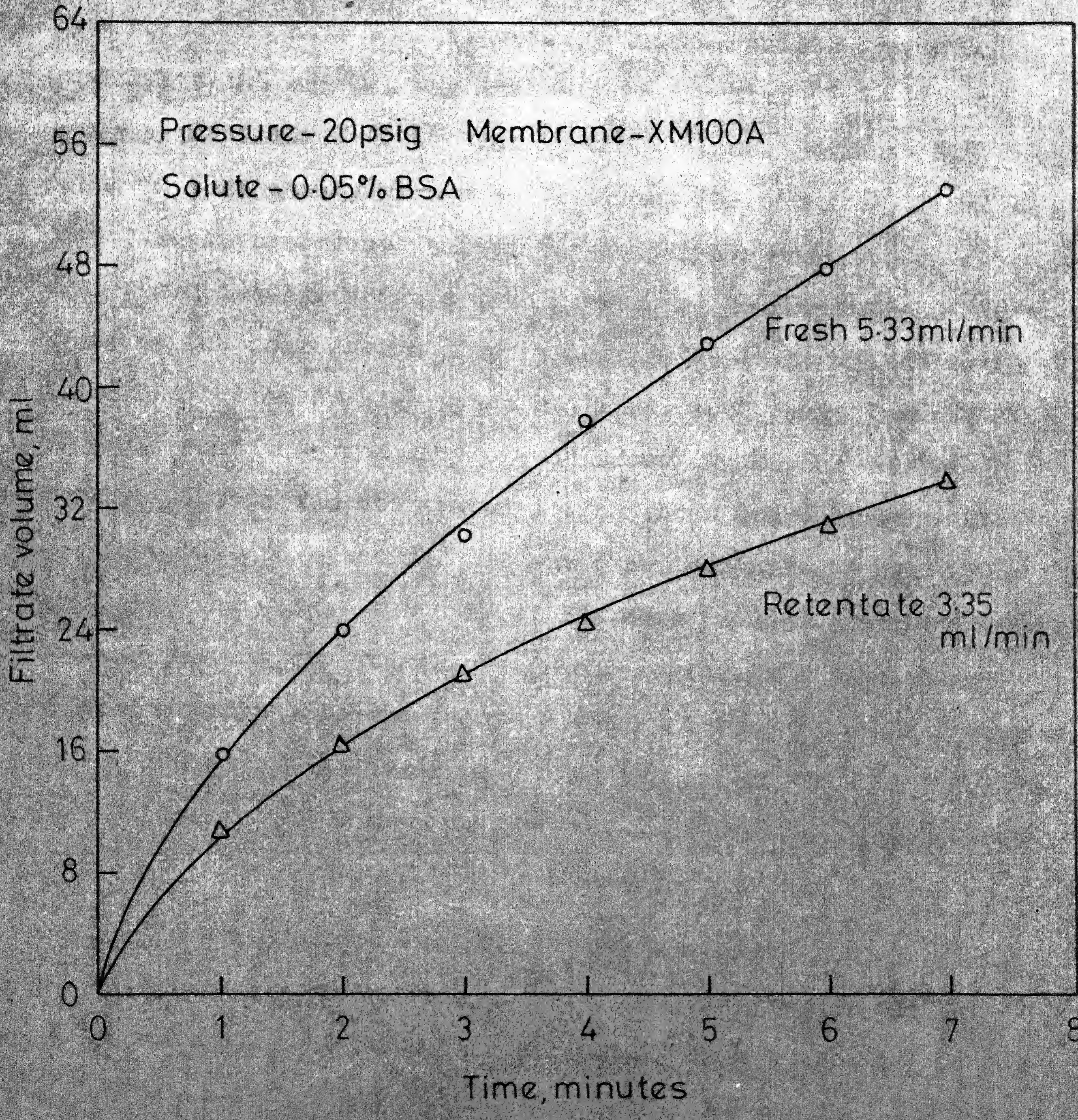


Fig. 4.25 - Effect of stirring - XM100A membrane (steady state)

macromolecules have been reported. The mechanical degradation of polystyrene and DNA was investigated by Zimm [75] using high pressure capillary and laboratory homogenizer. Nakano [61] has observed that during high speed stirring (30,000 rpm) of aqueous poly (vinylpyrrolidone) solution, the polymer chains were ruptured to lower molecular weights with decreasing concentration. In a study on the degradation of poly acrylamide (PAM) molecules in aqueous solution by high speed stirring (4000 rpm), Tsunoda [71] observed that the viscosity of the solution decreased after stirring. This was attributed to the shear degradation of PAM molecules due to stirring. It was experimentally verified that the molecular weight and size of PAM were reduced after stirring. The argument of structural change and degradation to smaller molecular weights of the solute due to shearing action has been used by Chian and Aschauer [19] also to explain the increased UF flux of frozen and thawed cheese whey over that of refrigerated whey.

Though these studies support the contention of change in the solute due to stirring, their applicability to the low speed (800 rpm) used in the present study is not known. It may be pointed out that this kind of anomalous behaviour with open membranes has not been reported in the UF literature. On the other hand VanOss et al. [73] have reported that stirred UF does in no way impair the biological activity of the protein

or alter the molecular weight distribution of proteins in a mixture of proteins. Hence, the hypothesis of change in solute due to stirring needs further confirmation. Unfortunately, no analysis of the physical properties (viscosity, molecular weight) or solute retention was done in this set of studies, so that the nature of solute change cannot be definitely identified.

The time required to reach steady state without stirring is also presented in Table 4.1. It can be seen from this table that the steady state is reached at a shorter period in the absence of stirring than when the cell solution is stirred. This behaviour is reasonable since the process of polarization is likely to be more severe in unstirred systems due to poorer back transport of solute.

4.2.6 Effect of Molecular Size:

Ultrafiltration membranes function, basically, as molecular sieves, separating solutes and solvent on the basis of relative molecular sizes. The most common index used for the choice of a suitable membrane is the molecular weight of the solute. Though molecular weight has been a satisfactory parameter for characterizing the ultrafilterability of a homologous series of molecules, such as globular proteins, each of the various other factors such as the size, shape, deformability of molecules and solute membrane interactions, influence the UF performance. All these factors cannot be

incorporated into a single parameter such as molecular weight.

A comparison of the UF results with the two solutes, BSA and Ovalbumin, in the present study, may give some idea, though not conclusive, of the effect of molecular size on the UF performance. Results indicate that under similar conditions, the fluxes and retentions with higher molecular weight solute, BSA, are higher than those for the lower molecular weight solute, Ovalbumin. The increase in retention with increasing molecular weight is logical since these membranes behave essentially as molecular sieves and it is well documented in the literature [5,12,15,29].

While the effect of molecular weight of solute on retention has been well investigated, there is very little information on its effect on the UF flux. In one study with human serum albumin, whole Bovine serum and gelatin, Porter [63] reported decreasing UF rates with increasing molecular weights. He attributed this to the lower diffusivities of the higher molecular weight solutes. But, in experiments with whole blood and plasma and polymer latex solutions, he found this to be invalid. In another study by Hopfenberg et al. [46] on the UF of surfactants with polyelectrolyte membranes, the UF flux could be observed to increase with molecular weight of the solute.

The results of the present study could, perhaps, be

explained in terms of the effect of molecular weight on the hydraulic permeability of the polarized layer. The high molecular weight solutes will have larger particle dimensions and porosity of the polarized layer of such solutes will also be higher. It was shown in Chapter 2 that the hydraulic permeability of the polarized layer is sensitive to the porosity and particle size. From equation (2.21) it is evident that the hydraulic permeability of the polarized layer of BSA should be more than that with Ovalbumin. Since the steady state UF rate is controlled by the polarized layer, the filtration rate with BSA should be higher than that with Ovalbumin.

Another feature to be observed is that the time required to reach steady state, shown in Table 4.1, for higher molecular weight solute is shorter compared with that for the lower molecular weight solute. This is most likely to be due to the higher retention of BSA which increases the concentration polarization modulus and results in a quicker attainment of the steady state. A higher flux level with a higher molecular weight solute will also hasten the formation of a gel layer so that steady state is reached earlier.

4.2.7 The Polarized Layer Resistance and the Pressure Drop in the Polarized Layer:

It was mentioned in Chapter 2 that a comparison of the

resistances of the polarized layer and the UF membrane will give an idea of the effect of concentration polarization on the UF performance. In this section the results of the present investigation are discussed on the basis of these resistances.

The resistances of the polarized layer and the membrane were calculated from the experimental flux values with protein solutions and the measured pure water fluxes using equations (2.17,2.19 and 2.20). The pressure drop in the polarized layer was then calculated from equation (2.20). These are presented in Tables 4.2 and 4.3 respectively.

The striking feature of Table 4.2 is the relative magnitudes of the polarized layer resistance and the membrane resistance. In all cases, the polarized layer resistance is much larger than the membrane resistance, which clearly proves that the polarized layer controls the UF performance. Further, Table 4.3 shows that a substantial fraction of the applied pressure is sustained by the polarized layer which means that the effective pressure drop for UF is greatly reduced resulting in a considerable loss in UF flux.

It is also evident from these tables that the polarized layer resistance is a function of the applied pressure, bulk concentration and the membrane permeability. It increases with increasing applied pressure and increasing bulk concentration

TABLE 4.2 RESISTANCE OF POLARIZED LAYER

Membrane	Applied Pressure (psig)	Membrane Resistance R_m	Polarized Layer Resistance, R_g, Psi.min/Cm.					
			Ovalbumin, percent			BSA, percent		
			0.05	0.5	0.05 unstirred	0.05	0.5	0.05 unstirred
PM30	10	20.0	118.31	180.0		68.5	146.67	
	20	29.41	161.07	288.05	230.59	93.29	217.5	278.59
	35	31.61	200.19	400.5		161.77	318.5	
XM100A	10	16.7	75.89	147.23		45.41	106.76	
	20	24.1	120.82	216.86	58.9	82.85	184.23	102.4
	35	25.5	190.55	354.97		148.68	295.65	
XM300	10	12.35	64.57	139.17		44.79	98.76	
	20	21.5	111.08	198.28	57.0	77.51	161.99	94.5
	35	21.1	180.05	343.48		139.45	283.25	

TABLE 4.3 PRESSURE DROP IN THE POLARIZED LAYER

Membrane	Applied Pressure (Psig)	Pressure drop in Polarized Layer, ΔP_G (Psig)					
		Ovalbumin, percent			BSA, percent		
		0.05	0.5	0.05 unstirred	0.05	0.5	0.05 unstirred
	10	8.55	9.0		7.74	8.79	
PM30	20	16.91	18.15	17.72	15.25	17.62	18.13
	35	30.23	32.44		29.78	31.85	
	10	8.2	8.98		7.31	8.65	
XM100A	20	16.67	17.99	14.2	15.41	17.69	16.20
	35	30.49	32.66		29.89	32.73	
	10	8.39	9.19		7.84	8.89	
XM300	20	16.68	18.04	14.6	15.66	17.67	16.35
	35	30.61	32.97		30.5	32.57	

but decreases with increasing membrane permeability. An increasing gel resistance with increasing pressure has been reported by Dejmek [27] and Copas and Middleman [21] also. But while Copas and Middleman have found the gel resistance to increase linearly with applied pressure for tubular cellulosic membrane system, Dejmek proposed, based on compression hypothesis that the increase in gel resistance should correlate with the pressure drop in the gel layer and not with the total applied pressure. Dejmek [27] confirmed this in experiments with an unstirred cell and obtained a 0.75 power dependence of gel resistance upon the pressure drop in the gel layer. The data of Table 4.2 and 4.3 also indicate that the increase in polarized layer resistance is not linear with the applied pressure but may fit a power relation with the pressure drop in the polarized layer. This means that the results of the present study also support the compression hypothesis as was pointed out in earlier sections. Similar compressible polarized layer model has also been used by Dorson et al. [29] to explain protein UF.

The compression hypothesis explains the variation of resistance of the polarized layer with bulk concentration also. According to this hypothesis, the resistance is proportional to the amount of deposit [27]. Therefore, an increase in bulk concentration, which increases the amount of deposit, will naturally lead to increased polarized layer resistance. This

becomes particularly evident at higher pressures.

Another aspect of importance in Tables 4.2 and 4.3 is that while the resistance of the polarized layer decreases with increasing membrane permeability, the decrease at higher pressures is much smaller than that at lower pressures. This means that, since polarized layer determines the UF flux, the UF flux will be nearly the same for all the membranes at high pressures. This invariance of flux with membrane permeability was discussed in an earlier section also.

The effect of agitation can also be explained in terms of the resistance of the polarized layer. It can be observed from Table 4.2 that the resistance of the polarized layer when the cell solution is not stirred is much higher than that for the stirred cell in the case of total retention membrane PM30 which points out to the necessity of stirring to improve the UF performance. Similar reduction in gel resistance due to convection promotion for total retention membrane has been shown by Copas and Middleman [21] also. On the other hand the polarized layer resistance for the stirred cell is seen to be higher than that without stirring with the open membranes, XM100A and XM300. The polarized layer resistance is a function of the hydraulic permeability which, in turn is sensitive to solute size and porosity of the layer. This confirms the postulation in the earlier section that the unusual flux

decrease observed with XM100A and XM300 membranes in stirred experiments compared with the unstirred experiments is a result of the change in the nature of the polarized layer. It can also be seen in Table 4.2 that the polarized layer resistance decreases with increase in the molecular weight of the solute. This can be explained by the increasing hydraulic permeability of the polarized layer of a higher molecular weight solute.

4.2.8 Comparison of Gel Layer Build up Model with Experimental Results:

A model of the gel layer build up, from the theory of classical filtration, was presented in Chapter 2 and relations were obtained for the steady state flux J_1 as a function of the filtrate volume. A comparison of the theory with the experimental results is presented in this section.

In classical filtration theory, with a cake being built up, an equation similar to equation (2.30) would be integrated so that filtrate volume 'V' is obtained as a function of time 't'. From the slopes and intercepts of a suitable plot, the specific resistance of the cake α and other parameters can be determined. For the stirred UF experiments of this work, the value of K_g in equation (2.30) is unknown. Further, equation (2.30) is quite complicated for an analytical solution. The utility of equation (2.33) is best understood in such a context.

For any given condition of experiment with Ovalbumin or BSA and PM30 membrane, values of τ_{ss}, ΔP_{gel}, V_{ss} and J_1 are available in Tables 4.1, 4.3 and 4.4 respectively. For a given pressure of operation, the data for the lowest concentration $\overline{C} = 0.05$ percent were chosen and $\alpha_0\eta$ was determined from equation (2.33) with the measured values of V_{ss}, τ_{ss}, ΔP_{gel}, A_M and J_1. Using this value of $\alpha_0\eta$ or $\alpha\eta$, the value of V_{ss} was predicted from equation (2.33) for the same pressure of operation but for a higher bulk concentration. The results of such calculations, assuming the cake to be incompressible ($n = 0$) and compressible ($n = 0.75$), are given in Tables 4.5 and 4.6 respectively. It may be observed from these tables that the deviations in the predicted filtrate volume V_{ss} from the experimental values are not considerable. Except for 0.1 percent BSA data at 20 psig, the agreement is particularly satisfactory considering that predictions are being made for V_{ss} values as low as 7 ml. with $\alpha\eta$ values determined from V_{ss} values as high as 36 ml. It is also to be noted that measuring V_{ss} and τ_{ss} from a plot introduces some error apart from that associated with the measurement of ultrafiltrate volume.

The volume of the ultrafiltrate, V_{ss}, collected upto time $t = \tau_{ss}$, rather than J_1, was predicted from equation (2.33) since J_1 is very sensitive, apparently, to small errors in V_{ss}. The lowest concentration of protein was used for determining

TABLE 4.4 MEASURED FILTRATE VOLUME AND FLUX AT STEADY STATE-INITIAL TIME STUDIES

Concentration of Protein,	ΔP Psig	Measured Filtrate Volume, V_{ss} ml.	Measured Flux, J_1 ml/cm^2 min.
0.05 percent Ovalbumin	10	15.75	0.0723
	20	24.5	0.105
	35	17.75	0.151
0.5 percent Ovalbumin	10	3.2	0.05
	20	5.6	0.063
	35	6.2	0.081
0.05 percent BSA	10	17.5	0.113
	20	32.0	0.163
	35	36.0	0.181
0.1 percent BSA	10	8.2	0.10
	20	11.0	0.138
0.5 percent BSA	10	3.2	0.06
	20	8.4	0.081
	35	7.1	0.1

TABLE 4.5 COMPARISON OF PREDICTED AND MEASURED FILTRATE VOLUME AT STEADY STATE FOR AN INCOMPRESSIBLE CAKE(n=0)

Concentration of Protein	ΔP Psig	$\alpha\ \eta \times 10^{-7}$ $\frac{\text{psi.cm.sec.}}{\text{gm.}}$	Predicted V_{ss} ml.	Measured V_{ss} ml.	Percent Deviation
0.5 percent Ovalbumin	10	5.35	2.83	3.2	-11.56
	20	5.88	4.9	5.6	-12.50
	35	10.15	4.64	6.0	-22.67
0.1 percent BSA	10	2.92	8.405	8.2	+ 2.5
	20	2.74	16.88	11.0	+53.5
	35	3.224	-	-	-
0.5 percent BSA	10	2.92	2.92	3.2	- 8.75
	20	2.74	7.87	8.4	- 6.3
	35	3.224	7.39	7.1	+ 4.1

TABLE 4.6 COMPARISION OF PREDICTED AND MEASURED FILTRATE VOLUME AT STEADY STATE FOR A COMPRESSIBLE CAKE (n=0.75)

Concentration of Protein	ΔP psig	$\alpha_0 \eta \times 10^{-7}$ $\frac{psi.cm.sec.}{gm.}$	Predicted V_{ss} ml.	Measured V_{ss} ml.	Percent Deviation
0.5 percent Ovalbumin	10	4.29	2.78	3.2	-13.1
	20	2.82	4.8	5.6	-14.2
	35	3.21	4.58	6.0	-23.6
0.1 percent BSA	10	2.83	8.38	8.2	+ 2.2
	20	1.41	16.56	11.0	+50.5
	35	1.01	-	-	-
0.5 percent BSA	10	2.83	3.05	3.2	- 4.6
	20	1.41	7.6	8.4	- 9.5
	35	1.01	7.01	7.1	- 1.2

$\alpha\eta$ values since the error in reading off V_{ss} from a graph of ultrafiltrate volume versus time is minimised with a higher value of V_{ss}. Further, the same applied pressure was used with varying bulk concentrations for checking the theory, since the regime of concentration polarization was more a function of pressure than of bulk concentration. In this context Table 4.5 shows that almost always the value of $\alpha\eta$ goes up with pressure, consistent with the filtration theory. But in Table 4.6 the $\alpha\eta$ values for $P = 10$ psig are higher than those at higher pressures. Since $P = 10$ psig is not in the gel polarized region, the theory may not be well applicable here. Probably the use of equation (2.36) may give a better agreement in this region. The relative usefulness of a compressible cake and an incompressible cake is therefore difficult to judge from Tables 4.5 and 4.6 since with regard to prediction of V_{ss}, the behaviour of both models are similar. Further, whether any value of n other than 0.75 would give a better fit to the data has not been investigated.

Another point to be observed from these tables is that the specific resistance α_0 of a polarized layer with Ovalbumin is much higher than that with BSA under similar conditions. This is consistent with the general implications of the postulation that the specific cake resistance, α, varies inversely with the square of the solute diameter (therefore the ratio $(\alpha_{Ovalbumin}/\alpha_{BSA}) \propto (d_{BSA}/d_{Ovalbumin})^2$) so that $\alpha_{Ovalbumin} > \alpha_{BSA}$.

It may thus appear, that the approximate, cake filtration type of model for gel layer build up in UF as presented in Chapter 2 has many desirable features and more rigorous analysis and experiments are called for.

It would be useful to compare the order of magnitudes of some of the values of $\alpha\eta$ given in Table 4.5 with what would be predicted from equation (2.24) for the given conditions of UF. Consider, for example, the value of $\alpha\eta = 10.15 \times 10^{7}\ \frac{\text{psi cm. sec.}}{\text{gm.}}$ for Ovalbumin at 35 psig. This is equivalent to a value of $\alpha\eta = 7.05 \times 10^{12}$ (seconds)$^{-1}$. The formula of $\alpha\eta$ from equation (2.24) is

$$\alpha\eta = \frac{K_1(1-\varepsilon)\eta}{\varepsilon^3 d^2\ \rho_s}$$

where the Carman-Kozêny constant K_1 has a value 180. Now from Figure 4.7, C_{gel}=32 gm/100 gm for Ovalbumin at 35 psig. Therefore $\varepsilon \cong 0.68$ and for a η value of water of 0.01 gm/cm sec. and ρ_s = 1 gm/cc and a value of $d_{Ovalbumin}$=42 Å, we get for $\alpha\eta$, a value of 10.2×10^{12} (seconds)$^{-1}$, which is only about 1.4 times greater than the value of $\alpha\eta$ from Table 4.5. Considering the uncertainities in the value of ε and d, this is quite reasonable. For example, a change of 0.05 in the value of ε from 0.68 to 0.73 will reduce the value of $\alpha\eta$ by 1.67 times. In addition, the exact hydrodynamic diameter of Ovalbumin molecules to be used here is uncertain and has to be determined from experiments assuming Carman-Kozeny equation to be valid. However, according to Colton et al. [76] the characteristic dimensions of Ovalbumin are 17.6x44.1 A^{o} and

and the minor half-axis dimension 17.6 A^o of an equivalent prolate ellipsoid was recommended by them for diffusion studies in dialysis. The choice of $d_{Ovalbumin} = 42\ A^o$ is to be considered in such a context. Further, from Tables 4.5 and 4.6, at 35 psig, $(\alpha_{Ovalbumin}/\alpha_{BSA})$ has the values of 3.16 and 3.18 respectively. Now the hydrodynamic ~~diameter~~ radius of BSA is 34 A^o [77]. If we use 25 A^o and 17.6 A^o for Ovalbumin, we will get $(\alpha_{Ovalbumin}/\alpha_{BSA})$ to be 1.86 and 3.7 resepctively. It is to be noted that the experimental ratio of 3.17 falls in between the predicted ratios.

It should be pointed out that essentially complete retention of the solutes through PM30 membrane was assumed in the calculations. A time averaged value of $C_p(t)$ could have been used in equation (2.27) and calculations could have been carried out by modifying equation (2.33) accordingly. This procedure would have altered the values of $\alpha\eta$. However, for PM30 membrane, it would not affect the calculated values of V_{ss} substantially, sincethe time averaged value of $C_p(t)$, $\overline{C}_p$, for BSA or Ovalbumin, is only around 1/7th of $\overline{C}$.

4.3 <u>Protein Ultrafiltration</u>: <u>Steady State Experiments</u>:

In the results discussed in the last section, the emphasis was on the UF behaviour of the system in the early stages of the process leading to a steady state. Experiments were also conducted to study the steady state UF performance of the system and the results are presented and discussed in this section. The variables studied for this purpose were, the concentration, the pH of the

solution and the membrane treatment with a non-ionic detergent, Teepol . The experiments were so performed as to study the effects, with systems of differing permeabilities. For a completely retentive system, BSA was ultrafiltered through PM30 membrane; for partial retention system, BSA and egg albumin were filtered through XM100A membrane and for total permeability system Hemoglobin was ultrafiltered through XM300 membrane. All experiments were conducted at 20 psig. for 1 hour.

4.3.1 Effect of Concentration:

Results of steady state UF studies as a function of concentration are presented in Table 4.7. To show the trend in UF performance, the results of steady state UF of BSA through XM100A membrane at different concentrations are plotted in Figure 4.26 as the volume of filtrate collected against time. It is evident from this figure that the trend is the same as was observed earlier in initial time experiments. The steady state fluxes were plotted against the concentrations in a semi-log plot as shown in Figure 4.27. This shows that equation (2.12) is obeyed and that the results are in agreement with the gel polarization model described in Chapter 2.

4.3.2 Effect of pH:

It is well known that pH has a significant effect on the properties of proteins, because of their dipolar character. For example, the solubility of proteins, in general, is minimum at the iso-electric pH. For this reason, pH becomes an important variable in the UF of protein solutions.

TABLE 4.7 THE EFFECT OF CONCENTRATION ON STEADY STATE ULTRAFILTRATION FLUX

Solute	Concentration percent	Membrane	pH	Steady state UF flux at 20 psig ml/cm^2 min.
	0.05			0.151
BSA	0.25	PM30	4.8	0.103
	1.0			0.063
	0.05			0.115
BSA	0.20	XM100A	4.8	0.087
	1.0			0.053
	0.05			0.087
Egg Albumin	0.25	XM100A	4.6	0.06
	1.0			0.042
	0.05			0.127
Hemoglobin	0.25	XM300	6.7	0.09
	1.0			0.061

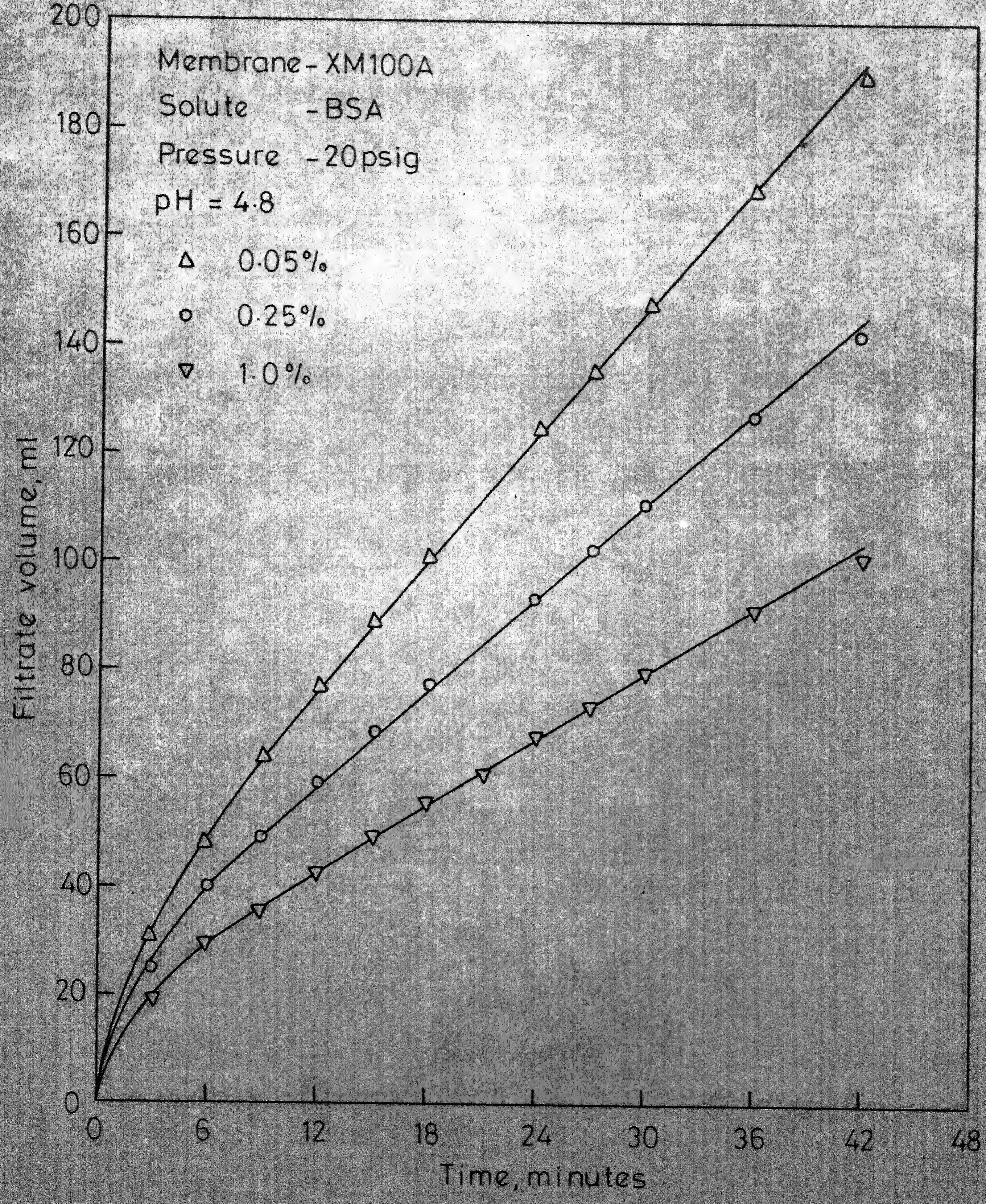


Fig. 4.26 - Steady state ultrafiltration results for BSA as a function of concentration.

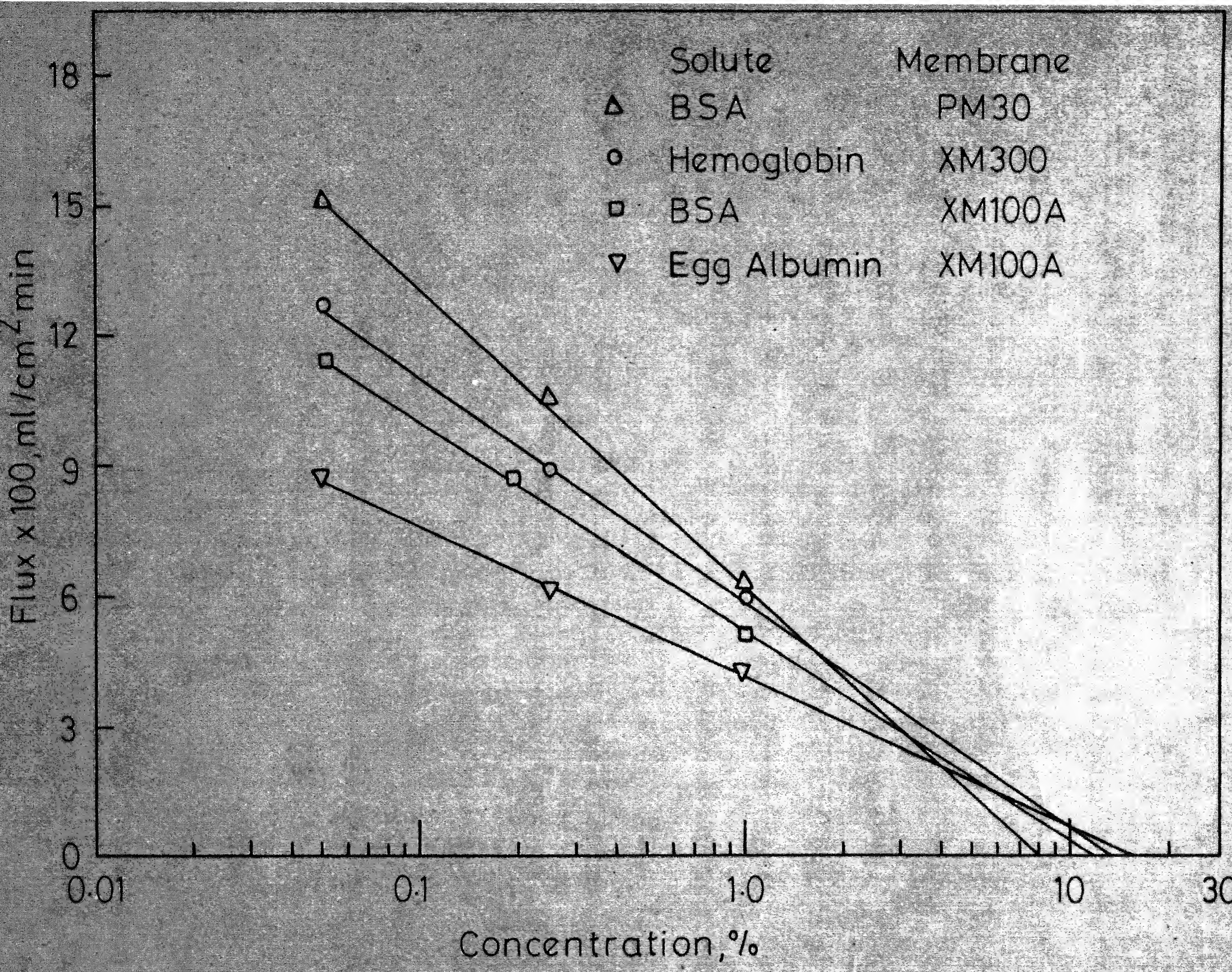


Fig. 4.27 - Effect of bulk concentration on ultrafiltration flux. (steady state)

To study the effect of pH on the UF behaviour, experiments were carried out with 0.25 percent protein solutions at different pH values. The results for UF of BSA through XM100A membrane shown in Figure 4.28 indicate the trend of the results. The steady state flux values are plotted as a function of pH, for steady state experiments in Figure 4.29 (a). The results indicate that the UF rate is reduced near the iso-electric pH and is higher at pH values both above and below the iso-electric pH. Initial time studies were also made on the effect of pH with 0.05 percent BSA and Ovalbumin through PM30 membrane and the results are plotted in Figure 4.29 (b). This figure also shows that the UF flux is minimum at the iso-electric pH and increases at pH values on both sides of iso-electric pH.

Though pH is an important variable in the UF of proteins, very little work has been done to study its effect on UF performance. In the UF of dilute albumin solutions with total retention membranes, Friedli et al. [36] found that the rate of filtration reduced sharply as the iso-electric point was reached. Lee and Merson [50] in their study of fouling in UF of cheese whey through PM10 membranes, have observed that acidification of whey increases the UF rates. They attributed this to pH induced changes in the state of β - Lactoglobulin, which constitutes about 50 percent of the whey protein. The marked effect of pH on the association/dissociation behaviour of

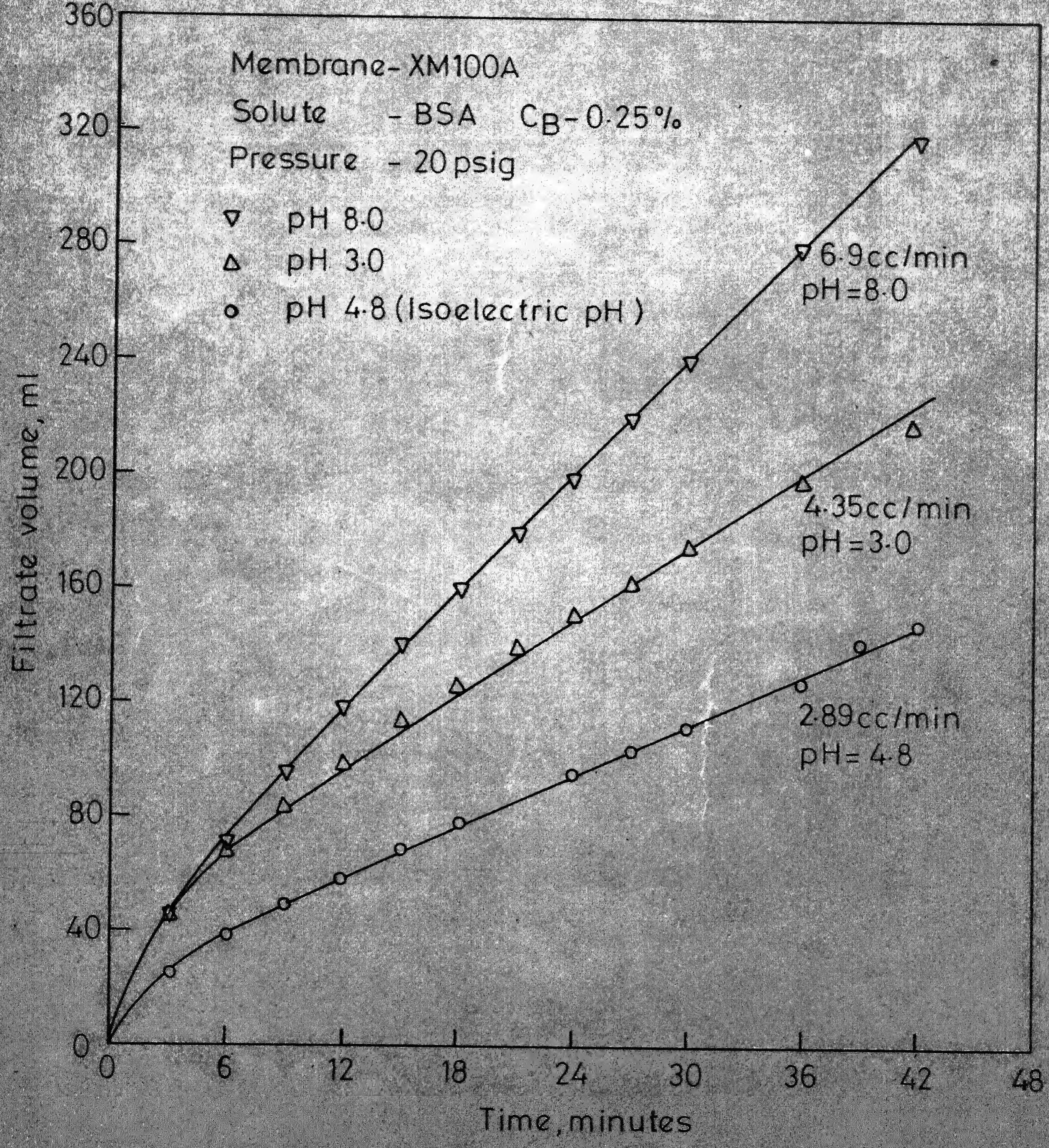


Fig. 4.28 - Steady state ultrafiltration results for BSA as a function of pH.

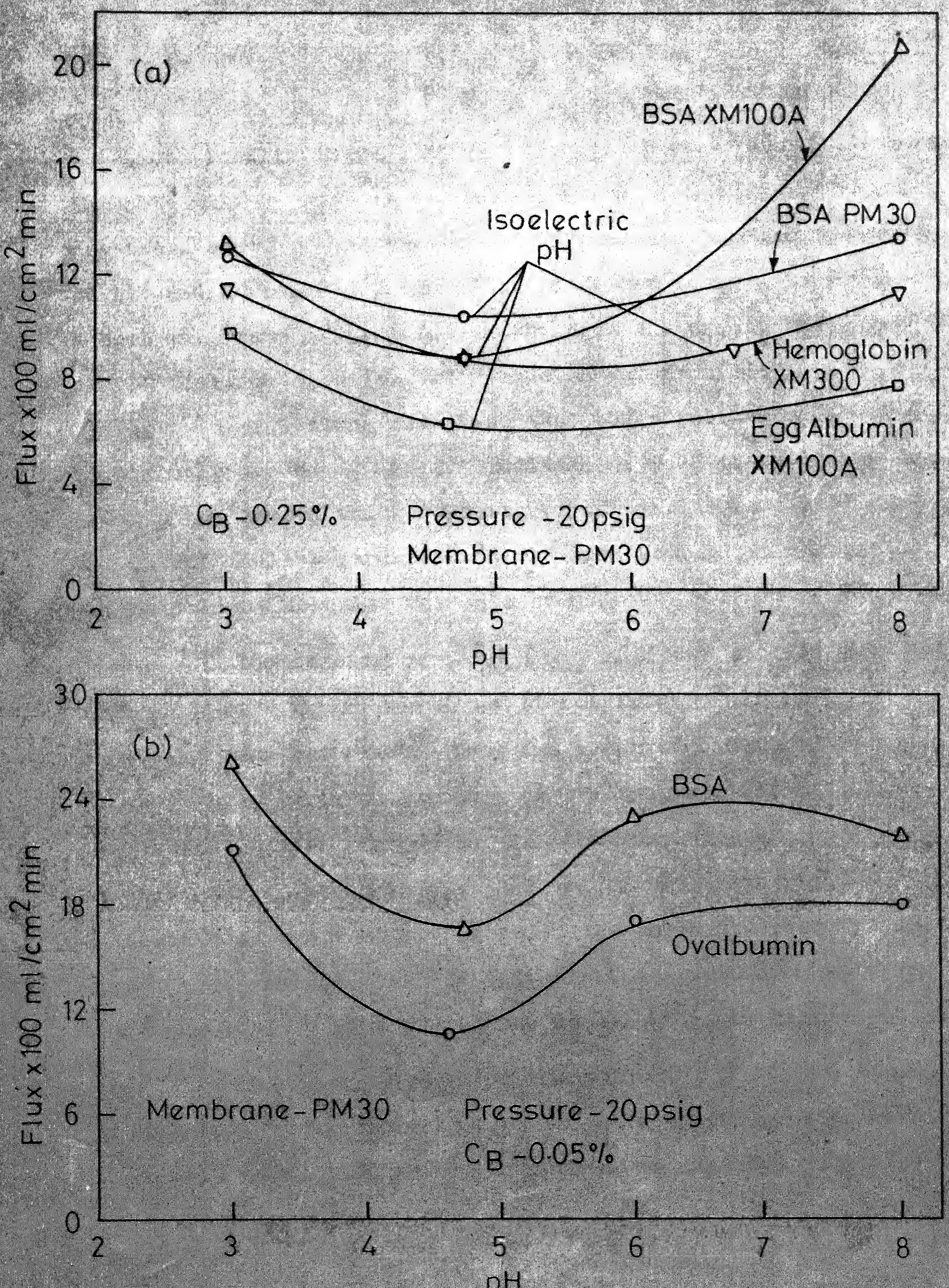


Fig. 4.29 - Effect of pH on ultrafiltration flux-(a) Steady state experiments (b) Initial time experiments.

β - Lactoglobulin is well known [49,54]. During ultrafiltration, the rate will be high if the proteins are either maintained in a dispersed state or if the deposits formed are porous. According to Lee and Merson [50], the addition of chemicals to proteins alters the state of proteins and changes the amount and structure of the fouling deposits. They have shown, from electron micrographs of fouling deposits, that the structure of deposits is strongly dependent on pH. Addition of NaOH destabilized the protein and caused thick deposits of a granular matrix to form a non-porous fouling layer. Acidification stabilized the protein and only light deposits were observed.

The dependence of UF flux on pH was studied also by Fane and Fell [33] in the UF of starch factory effluents through non-cellulosic membranes. They had observed a minimum in flux at a pH of 4-5 with a maximum at a pH of approximately 3.0, which they attributed to changes in the behaviour of proteins due to pH variation. They have also pointed out that minimum in UF flux is thought to occur at the iso-electric pH, as the proteins then agglomerate and have lowered diffusivities. Similar behaviour has been observed with proteinaceous solutions by Forbes [34] also.

The variation of UF rate with pH could also, possibly be explained by the effect of pH on the adsorption of proteins. It is well known that protein molecules get adsorbed to the

membrane surface during ultrafiltration. Any factor which alters the adsorption characteristics of the proteins will correspondingly affect the UF performance also. The adsorption of proteins on synthetic surfaces has been well studied and it has been reported that the adsorption reaches a maximum near the iso-electric pH [55,62]. Dillman and Miller [28] have studied the adsorption of serum proteins on polymeric membrane surfaces and have observed that the adsorption increases as the iso-electric pH is approached. Clearly, an increasing adsorption will increase the amount of deposit and thereby decrease the UF flux.

It can be seen that the results on the effect of pH on the UF performance reported in the present study are comparable with those reported in the literature and could be explained in terms of a change in the state and behaviour of the proteins. The adsorption charectristics of the proteins on the UF membrane used were not however separately studied in this work so that their contribution is unknown.

4.3.3 Effect of Detergent Treatment:

One of the methods suggested by the membrane manufacturers for the removal of adsorbed proteins is to clean the membrane with a dilute detergent solution. This method of cleaning was tried early in this study. The membrane, after a protein run, was kept in a dilute solution of non-ionic

detergent, Teepol (a detergent based on secondary alkyl sulphates and alkyl aryl sulphonates) for a few minutes and then washed with water. After this cleaning procedure, when double distilled water was passed through the membrane to check its pure water permeability, a large increase in the rate of filtration was observed. In fact, this rate was higher than the original rate of pure water filtration. This unusual behaviour in pure water filtration following the treatment with detergent gave rise to a suspicion that detergent treatment may alter the filtration performance of the membrane and led to the investigation of the effect of detergent treatment on UF performance.

This effect was studied with a XM100A membrane. The membrane was kept in 40 ml. of 5 percent (V/V) solution of Teepol for two different time periods, 30 minutes and 3 hours, washed with water and the filtration performances of double distilled water, 0.5 percent polyethylene glycol (PEG) and 0.25 percent BSA solution were studied. The results are presented in Figures 4.30, 4.31 and 4.32.

The results indicate that the membrane treatment with detergent enhances the UF rate in all the cases. This type of increase in rate of ultrafiltration due to detergent treatment has not been reported in the literature. Even in UF studies where detergents have been used to clean the membranes, there has been no mention about improvement in membrane performance.

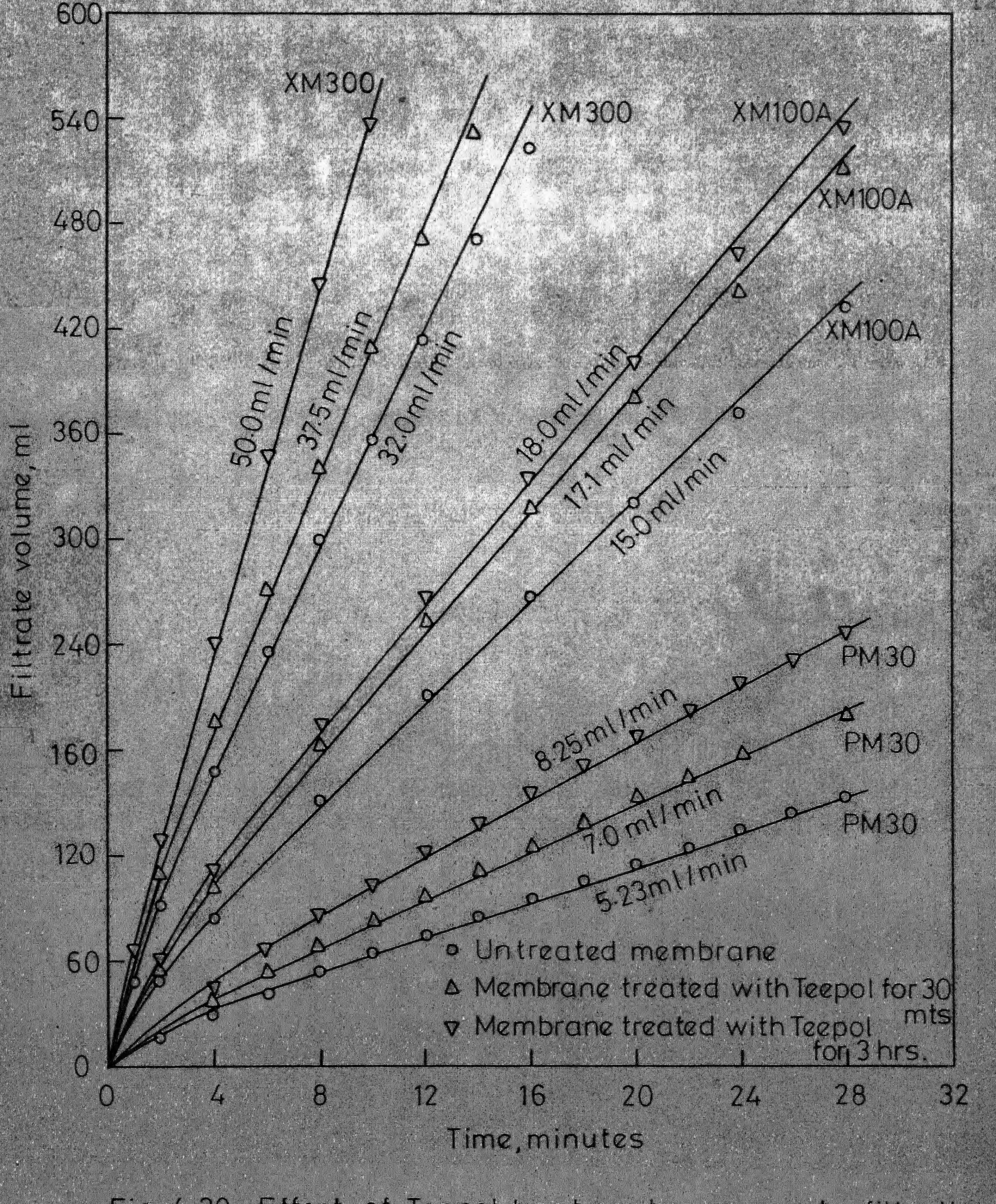


Fig. 4.30 – Effect of Teepol treatment on pure water filtration.

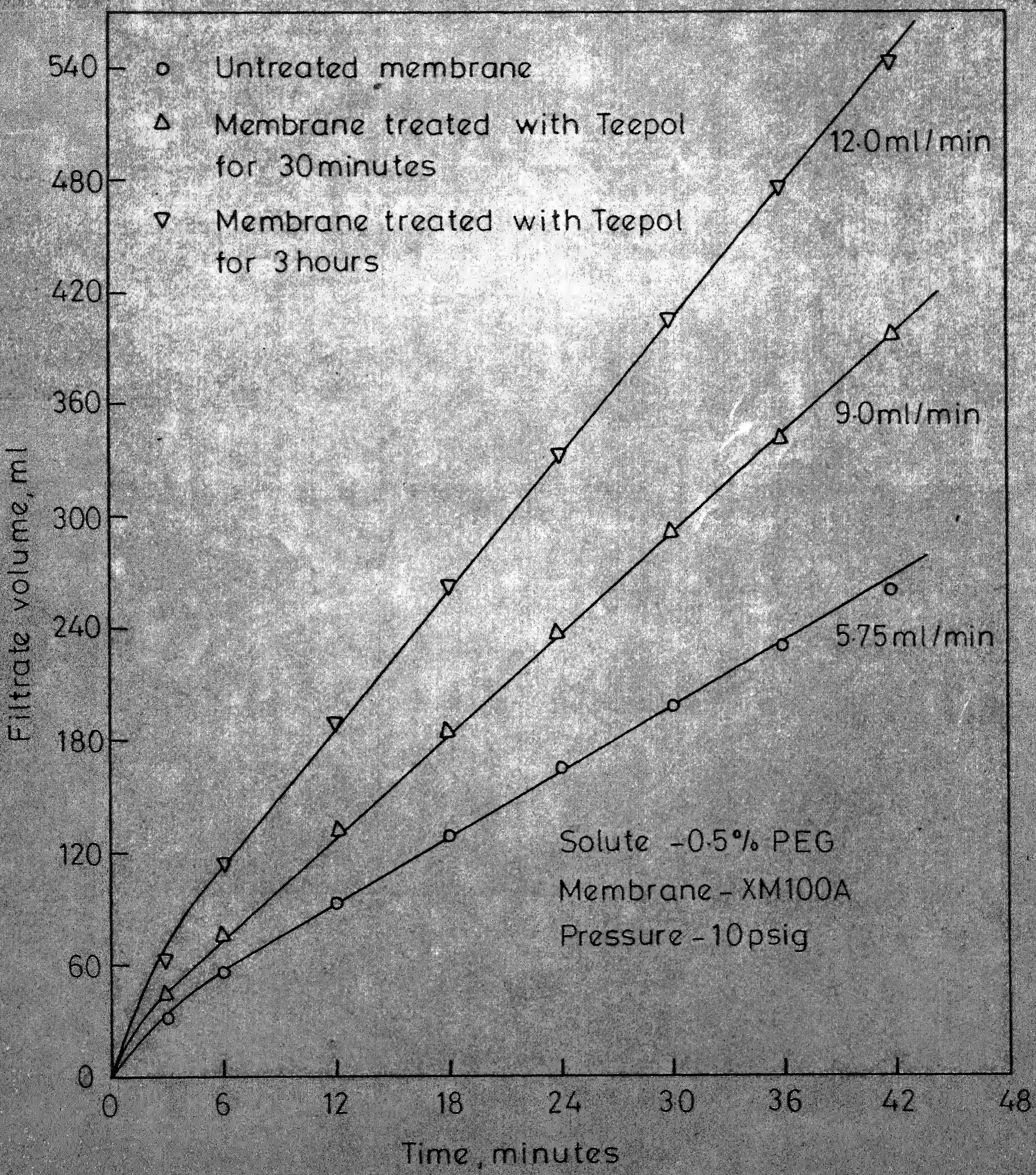


Fig. 4.31 - Effect of Teepol treatment on the ultrafiltration of PEG.

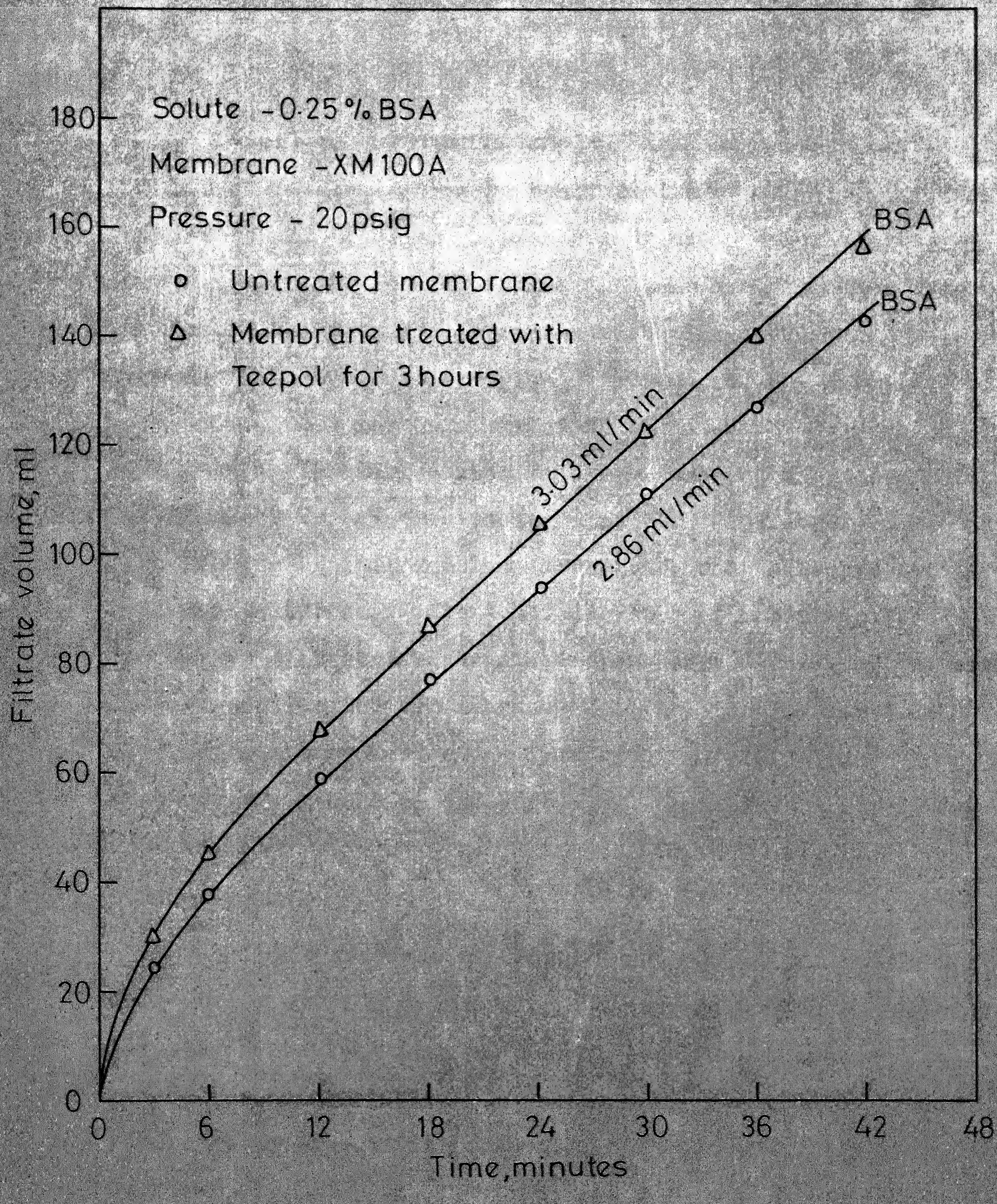


Fig. 4.32 - Effect of Teepol treatment on ultrafiltration of BSA.

UF of detergents has been studied with membranes capable of retaining them by Bhattacharya et al. [10,11], Grieves et al. [44] and Hopfenberg et al. [46]. They have observed that the results follow the same trend as with other solutes, i.e., the rate decreases with time. The gel polarization model has been found to describe the results adequately. But in the study of UF of laundry waste constituents with negatively charged PSAL membrane (non-cellulosic skin on cellulosic backing), Bhattacharya et al. [10] observed an increase in water flux with a detergent, sodium lauryl benzene sulphonate (LAB) and with a mixed system of LAB and polyphosphates over that with solute free water. This was beleived to have been caused by membrane swelling. Similar membrane swelling and increased water flux with increasing soap concentrations were also observed by Laconti et al. [48] in experiments with synthetic wash water through negatively charged membranes.

The increase in UF rate after treatment, observed in this study, could also probably, be explained by the swelling of the polyelectrolyte membrane due to detergent treatment and consequent change in the pore structure. Swelling of cotton fibers by treatment with detergents has been reported by Betrabet et al. [9]. They had observed that Triton B (Trimethyl benzyl ammonium hydroxide) is a powerful swelling

agent for cotton fibers and it opens up the fine structure of cellulose considerably without significantly altering its basic structure or physical properties.

The effect of detergent treatment on retention of BSA is also presented in Figure 4.31. The decrease in retention when the membrane was treated with detergent seems to further confirm the argument of swelling of membrane and opening up of its pores.

Another aspect to be observed from these figures is that while there is a significant increase in UF rate with distilled water and PEG solution, the improvement in rate due to detergent treatment is only marginal with the protein solution. This indicates that the mechanism by which the detergent treatment improves the membrane performance is a function of the solute also. The behaviour with proteins may be due to some interaction between the protein and the adsorbed detergent during ultrafiltration. Interactions between proteins and detergents have been reported by Green [43].

It is necessary to note here that cleaning and passage of distilled water through the membrane, after an UF run with detergent treated membrane was complete, brought the membrane permeability back to its original value. In general this required about 1 hour.

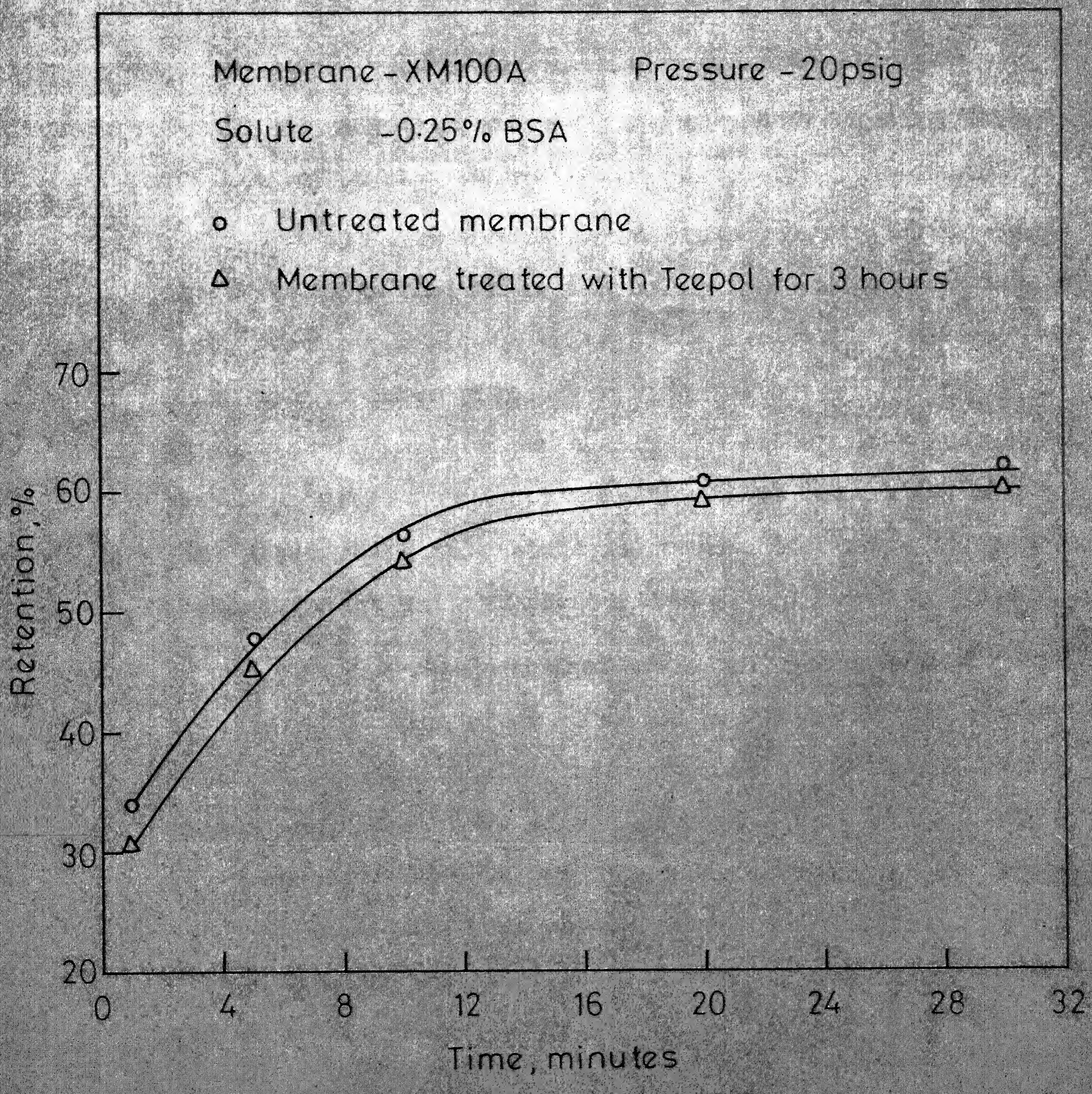


Fig. 4·33 - Effect of detergent treatment on solute retention.

CHAPTER 5

CONCLUSIONS AND SCOPE FOR FUTURE WORK

A summary of the conclusions reached in this study are presented in this section.

As a result of macrosolute polarization, the UF flux decreases with time while the solute retention increases with time, reaching a steady state after a certain time interval. Polarization takes place even with quite open membranes and affects their performance also. The retention values reported by the manufacturers for the membranes of this study are valid only after the steady state is reached and there is some solute leakage in the initial period even with apparently tight membranes.

The time required to attain a steady state in UF flux, τ_{ss}, is a function of the applied pressure, solute concentration, membrane permeability, solute molecular size and stirring conditions. The value of τ_{ss} increases with pressure at low pressures but decreases at higher pressures. At all pressures, τ_{ss} decreases with increase in solute concentration and solute size while, it increases with increasing membrane permeability and stirring.

The results agree well with the gel polarization model proposed by Michaels at higher pressures and at higher bulk solute concentrations, i.e., in the gel polarized

region. In this region the UF flux is invariant with pressure and is almost independent of the membrane permeability and varies linearly with the logarithm of bulk concentration. The solute retention, in this region, is nearly invariant of pressure and increases with increasing bulk concentration while decreasing with increase in membrane permeability.

In the pre-gel polarized region, the flux increases with increasing pressure and membrane permeability but the width of the pressure dependent region is a function of the bulk concentration and membrane permeability. The threshold pressure at which the gel polarization takes place is lower at higher bulk concentrations and for higher permeability membranes.

The polarized layer is compressible as is indicated by the effect of pressure and solute concentration on the retention behaviour and on the resistance of the polarized layer.

The calculated values of resistance of the polarized layer and pressure drop in the polarized layer indicate that the polarized layer controls the UF performance and most of the applied pressure is sustained by the polarized layer. The resistance of the polarized layer increases with pressure and solute concentration but decreases with increasing membrane permeability.

With totalretention membranes, stirring results in

an improvement in the rate of filtration. But with open membranes stirring was observed to decrease the rate of filtration, which may be due to degradation of proteins to lower molecular weights as a result of hydrodynamic shear.

With the solutes used in this study,both UF flux and solute retention were higher for higher molecular weight solutes. The higher flux with higher molecular weight solutes is likely to be due to the increased permeability of the polarized layer formed with such solutes.

The solution pH has a significant effect on the UF flux of proteins. The flux is minimum at the isoelectric point (IEP) of the proteins and increases at pH values on both sides of it. This could probably be the result of pH induced changes in the state and behaviour of the proteins and due to the increased adsorption of proteins at IEP.

The membrane treatment with a non-ionic detergent prior to filtration increases UF flux and decreases the solute retention, probably as a result of swelling of the membrane on treatment with detergent and consequent changes in the pore structure.

The theoretical model for the gel layer build up based on the classical filtration theory proposed in this study compares favourably with the experimental results as indicated

by the agreement between the predicted and the measured volume of ultrafiltrate collected when the steady state is attained.

As is evident from the discussion of the results of this study, further work is necessary to gain a better understanding of protein UF and the problem of gel polarization. Also, some of the effects investigated, need further study. Some suggestions are made in this section towards this direction.

Initial time studies should be carried out with a broader range of pressures and solute concentrations than those used in this study to get a clearer picture of the polarization process.

Investigations on the nature of deposits on the membrane after the experiment, particularly its weight and structure, should be studied.

The membranes used in this study were supposed to have a narrow pore size distribution and hence the pores were not expected to be clogged. But with more open membranes and membranes with broader pore size distribution, clogging of the pores might affect the results. The clogging behaviour of various membranes should be studied so as to isolate its effects, if any, from that of gel polarization. Also, other membrane materials should be investigated to study the effect of specific solute-membrane interactions.

The effect of stirring needs further confirmation. Different stirring speeds should be used to study the effect of stirring on the UF performance. The viscosity and molecular weight distribution before and after stirring may be measured to confirm the hypothesis of change in the structure of solute due to stirring.

The change in the structure of the deposit with variation in pH should be investigated to ascertain the effect of pH. The adsorption of proteins on membrane surfaces and its variation with pH need to be studied separately. The effect of other chemical additives to change the structure of proteins as well as protein deposits may also be investigated.

The hypothesis of swelling of membrane on treatment with detergent should be studied further by examination of the membrane pore structure.

The model of gel layer build up proposed in this study could be made more rigorous. The theory should be tested with the results for XM 100A and XM 300 membranes also. More experiments at lower pressures will be needed to list the theory in the pre-gel polarization region.

The effect of a forming gel layer on the solute retention should also be part of a comprehensive model for gel layer build up. The retention with respect to gel-forming

solute as well as any other tracer solute should be the subject of further modelling.

Any such model should also seek an explanation for the different estimates of time required to attain the steady state in UF flux and solute retention. The discrimination between a compressible and an incompressible cake model may also be carried out.

Ultrafiltration in geometries and flow systems with well characterized mass transfer coefficients should be preferred in any future investigation. This is likely to be useful in verifying some of the features of any filtration type model.

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